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Golub Medvešek, Ivana

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DOCTORAL THESIS

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DOCTORAL THESIS

Supervisor: Hrvoje Dodig, Ph.D.
Co-supervisor: Nenad Leder, Ph.D.

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IMPRESUM

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Supervisor: Hrvoje Dodig, Ph.D.,
assistant professor, Faculty of Maritime Studies, University of Split

Co-supervisor: Nenad Leder, Ph.D.,
assistant professor, Faculty of Maritime Studies, University of Split

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DATA ON EVALUATION AND DEFENCE OF THE DISSERTATION

Doctoral thesis evaluation committee:

1. prof. Pero Vidan, Ph.D., president,
   full professor, Faculty of Maritime Studies, University of Split
2. prof. Blagovest Belev, Ph.D., member,
   full professor, Nikola Vaptsarov Naval Academy, Varna, Bulgaria
3. Joško Šoda, Ph.D., member,
   associate professor, Faculty of Maritime Studies, University of Split
4. Igor Vujović, Ph.D., member,
   associate professor, Faculty of Maritime Studies, University of Split
5. Tina Perić, Ph.D., member,
   assistant professor, Faculty of Maritime Studies, University of Split

Doctoral thesis defense committee:

1. prof. Pero Vidan, Ph.D., president,
   full professor, Faculty of Maritime Studies, University of Split
2. prof. Blagovest Belev, Ph.D., member,
   full professor, Nikola Vaptsarov Naval Academy, Varna, Bulgaria
3. Joško Šoda, Ph.D., member,
   associate professor, Faculty of Maritime Studies, University of Split
4. Igor Vujović, Ph.D., member,
   associate professor, Faculty of Maritime Studies, University of Split
5. Tina Perić, Ph.D., member,
   assistant professor, Faculty of Maritime Studies, University of Split

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STATEMENT ON DOCTORAL THESIS ORIGINALITY

I declare that my doctoral thesis is the original result of my work and that it clearly states and cites the references of contributions and papers by other authors[1]. I also declare that I have fulfilled all the conditions for initiation of the procedure of evaluation and defense of the doctoral thesis, including those related to the publishing and presentation of papers from the doctoral thesis research area[2].
I declare that the proposed doctoral thesis has been formatted according to the Instructions for doctoral thesis formatting.

Ivana Golub Medvešek

(first and last name of doctoral candidate, signature)

SUPERVISOR BIOGRAPHY

Hrvoje Dodig received a B.Sc. EE degree from the Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split in 2002. He was awarded the Chevening scholarship grant for postgraduate study in computational electromagnetics at the Wessex Institute of Technology. He received Ph.D. EE degree from the WIT, UK in 2012. From 2013 to 2016 he was with the Department of Radar Technology at the Naval Electronic Center, Croatia, and he was the head of hardware and software design of military communication equipment. Since 2016 he is Faculty of Maritime Studies, Split. He became assistant professor in 2018 when he also became Dean of Research.

CO-SUPERVISOR BIOGRAPHY

Nenad Leder earned his doctor's degree in 2004. His first employment was in 1982 at the Oceanographic Department of the Hydrographic Institute in Split. In the period 2014-2017 he was the Director of the Hydrographic Institute. From June 1, 2017 until today, he has been employed as a professor at the Faculty of Maritime Studies. During his career he has been involved as member of the expert group of the International Hydrographic Organization (IHO) in Monaco. During two ordinary sessions of the IHO he was a member of the Croatian delegation, while at the 5th Extraordinary International Hydrographic Conference that took place in Monaco in April 2017, he was the head of the Croatian delegation. He has published 146 scientific and professional papers and has participated in more than 250 studies and project reports in the field of hydrography, geophysics and oceanology.

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ABSTRACT

Hydrographic survey or seabed mapping plays an important role in achieving better maritime safety, especially in coastal waters. Due to advances in survey technologies, it becomes important to choose well-suited technology for a specific area. Moreover, various technologies have various ranges of equipment and manufacturers, as well as characteristics. Therefore, in this thesis, a proposed method of a hydrographic survey, i.e., identifying the appropriate technology, has been developed. The method is based on a reduced elimination matrix, decision tree supervised learning, and multicriteria decision methods. The available technologies were: SBES (research vessel), SBES+SSS (research vessel), MBES (research vessel), MBES (research vessel)+SBES (small boat), LIDAR (UAV), SDB (satellite sensors) and they are applied as a case study of Kaštela Bay. The optimal technology for Kaštela Bay study case was MBES (research vessel) and MBES (research vessel) + SBES (small boat) with a score of 0.97. Then with a score of 0.82 follows the SDB technology. Other available alternatives have a significantly lower score. It is a small evident difference between the three alternatives SBES (research vessel), SBES+SSS (research vessel), and LIDAR, which have a WSM score in the range from 0.58 – 0.65.

Key words: International Hydrographic Organisation, survey categories, IHO regions, stranding, supervised learning, decision tree, hydrographic survey, weighted sum model, multidecision, criteria, survey technologies.

CONTENTS

1. INTRODUCTION

1.1. Research problem, subject, and object of the research

The economy of maritime affairs is large and diverse. An increasing economic activity across various sectors is evident. Hence, in support of the safe and effective use of the sea resources, a better understanding of hydrographic survey and its appropriate realization is essential.

Hydrography is the branch of applied science which deals with the measurement and description of the physical features of oceans, seas, coastal areas, lakes, and rivers, as well as with the prediction of their change over time, for the primary purpose of safety of navigation and in support of all other marine activities, including economic development, security and defence, scientific research, and environmental protection [1], [2].

In order to support safe and efficient navigation of ships, hydrography underpins almost all activities associated with the sea. Furthermore, this includes exploitation of resource (e.g., fishing, minerals, etc.), environmental protection and management, maritime boundary delimitation, national marine spatial data, infrastructures, recreational boating, naval defence and security, tsunami flood and inundation modelling, coastal zone management, tourism and marine science [1].

Hydrographic survey is considered as a part of hydrography. It refers to sea depth measurement, marine geodesy, geodetic and other surveys of an object (on the coast, in the sea, on the seabed and underwater), geology and geophysics of the sea, oceanology, marine environmental protection activities (the part which refers to hydrography and hydrographic – navigational insurance of navigation), research, etc. [2].

The primary purpose of hydrographic surveying is to collect data to be entered into new editions of nautical charts and navigation publications [3]. Therefore, nautical charts must be reliable. The fundamental determinants of reliability are the accuracy, timeliness, and unambiguity of the information content of nautical charts and navigation publications [4].

To maintain the accuracy and reliability of nautical charts and navigational publications, the signatory countries to the United Nations Convention on the Law of the Sea - *UNCLOS* undertake the necessary hydrographic, oceanographic, and other research in the maritime space of sovereignty, to guarantee safe maritime traffic and uniformity of nautical charts and navigation publications.

Shortcomings exist in creating nautical charts and navigation publications and in their lifetime. Hydrographic organizations rely on data obtained until two centuries ago when hydrographic survey methods were extremely limited [5].

The research problem is the deficiency of valuation methods for identifying the most appropriate technology for a specific hydrographic survey area. The subject of research can be represented by important determinants, as follows:

- Evaluate IHO recommended methods;
- Analyse and evaluate the state of hydrographic surveys in the world;
- Investigate the disparity between IHO regions;
- Set parameters as a function of a cost of hydrographic survey techniques;
- Propose distribution of hydrographic survey area characteristics;
- Develop and create an elimination matrix for suitable technologies regarding the survey area;
- Create a decision tree model;
- Perform multi-criteria decision optimization and
- Prove applicability and implementation of the proposed approach.

Based on the problem and the subject of research, the object of this research is determined. It refers to the identification, analysis, and selection of optimal technologies for hydrographic survey.

1.2. The working hypothesis, purpose, and general objectives of the research

The developed model for achieving selection of optimal technologies for hydrographic survey is expected to increase the hydrographic survey scope. It is also expected that the required hydrographic survey quality criteria will be met. Based on the exposed problem, subject, and object of the research, the following working hypothesis is set:

By applying the proposed model for selection of optimal technologies for hydrographic survey it possible to increase the hydrographic survey scope while meeting the required hydrographic survey quality criteria.

Based on such a working hypothesis, the auxiliary hypotheses are formulated:

AH 1: IHO standards for conducting hydrographic surveys and their recommendations are becoming rigorous.

AH 2: Disparity between IHO regions exist.

AH 3: The correlation between hydrographic survey and navigation safety exists.

AH 4: It is possible to develop the elimination matrix to select suitable technologies that may be taken for further consideration regarding the characteristics of the survey area.

AH 5: The results of the elimination matrix can be used to create a decision tree, and it can be applied in every hydrographic survey area.

AH 6: Determining the optimal criteria for hydrographic surveying to ensure adequate quality of hydrographic survey in the optimization process.

AH 7: By applying the proposed method, it is possible to achieve/identify optimal technologies.

The limitations that are placed before this working hypothesis and auxiliary hypothesis are:

- Diversity of technical - technological equipment of hydrographic organizations;
- Different level of knowledge of hydrographic staff and
- Different budgets of hydrographic organizations.

The purpose of this research is to prove the applicability and validity of the proposed hydrographic survey optimal technologies selection model in any hydrographic survey area while meeting the required hydrographic survey quality criteria.

The general objectives of the research are:

- To analyse the scope of hydrographic survey implementation in the world;
- To determine and analyse the parameters in the function of the costs of hydrographic survey techniques;
- To propose the method on hydrographic survey technology selection based on the decision tree supervised learning procedures and
- To propose a method that will satisfy the required criteria.

1.3. Previous research

Current technical and technological solutions in the implementation of a hydrographic survey show a high degree of development. It is reasonable to assume that the cost is one of the main factors affecting the implementation of a hydrographic survey. The problem of costs in conducting a hydrographic survey has already been recognized in the previous scientific and professional literature. The researchers have not shown a tendency to analyse, study or propose the reduction of the cost of hydrographic activity by rationalizing hydrographic survey quality criteria such as budget foundations, time of conducting the survey and/or accuracy.

The authors mainly deal with the analysis of the impact of technology on the accuracy and coverage of hydrographic measurement. They suggest applying a combination of different systems and sensors to improve the accuracy of hydrographic survey data. The accuracy and cost-effectiveness are constantly improved by incorporating new technologies. They also study the economic benefits of conducting hydrographic surveys, accurate nautical charts, and navigational publications. Finally, the cost of training hydrographic surveyors is discussed too.

Smith A.R. et al., (2000), in the paper "*Airborne Lidar and Airborne Hyperspectral Imagery: A Fusion of Two Proven Sensor for Improved Hydrographic Surveying"* [6] investigate the application of airborne laser scanning technology, *Airborne Light Detection and Ranging - Airborne LIDAR*, and spectrometry in hydrographic measurement. They indicate the financial viability of its use in the coastal area.

They suggest that the accuracy can be improved and the cost and the time required for data collection can be reduced by combining a hyperspectral remote sensor *Compact Airborne Spectrographic Imager - CASI* and a bathymetric laser system *Scanning Hydrographic Operational Airborne Lidar Survey - SHOALS*.

Guenther C.G. et al., (2000), in the paper *"Meeting the Accuracy Challenge"* [7], on the technical side, analyse the air lidar system in the context of hydrographic survey accuracy and financial viability. Guenther C.G. (1996) also investigates the probability of detecting small objects on the seabed in the scientific paper "*Obstruction Detection and Data Decimation for Airborne Laser Hydrography*" [8]. He draws attention to the importance of probing spacing in aerial laser scanning. He concludes that the detection of seabed characteristics can be improved by reducing the average linear spacing of hydrographic lines or reducing the laser pulse width. The paper reiterates the financial advantage of using an aerial lidar system in conducting hydrographic surveys.

Hegrenaes Ø. et al., (2010), in the paper "*Horizontal Mapping Accuracy in Hydrographic AUV Surveys"* [9], analyse the horizontal accuracy of the cartography achieved by integrated hydrographic *Autonomous Underwater Vehicles - AUV*. They concluded that AUV systems with appropriate acoustic positioning are financially viable and can meet IHO standards for the prescribed accuracy of horizontal positioning in a particular category area.

In order to achieve greater consistency of the data obtained by hydrographic survey with the actual data on nautical charts and navigational publications, a reambulation procedure was proposed by Kasum J. (2002) in his doctoral dissertation "*Contribution to the optimization of reambulation using electronic and information technologies*" [10]. He points out the importance of reambulation to collect maritime safety information to maintain nautical charts and navigation publications. He concludes that, according to the proposed model of working procedures and the algorithm for determining the type of reambulation and the frequency of regular reambulation, the reambulation procedure can reduce costs of hydrographic organizations.

Hampson R. et al., (2011), in the paper "*A Low-Cost Hydrographic Kayak Surveying System*" [11], develop and describe a kayak hydrographic survey system. They emphasize its easy application near the coast and in hard-to-reach places. They compare the obtained results in particular areas. They conclude that kayak systems can reduce the cost of hydrographic surveying compared to conventional surveying systems.

Waddington A., (2014), in the paper "*A Cost-Benefit Analysis for the Application of a Multi-Sensors Approach to Near Shore Hydrography*" [12], points out that the *Multibeam Echo Sounder System - MBES* is generally most commonly used to perform hydrographic surveys. He emphasizes that its use at depths < 10 m takes a lot of time and increases measurement costs. It proposes using satellite data combined with airborne laser scanning technology *Airborne Light Detection and Ranging - Airborne LIDAR*.

Brisson L.N. et al., (2014), in the paper "*Interferometric Swath Bathymetry for Large Scale Shallow Water Hydrographic Surveys*" [13], show state of the art performance capabilities and cost savings provided by *Phase Differencing Bathymetric Sonar Systems - PDBS*, in particular EdgeTech 6205. They compare the costs of hydrographic surveys using MBES and PDBS in three Florida ports. They conclude that the survey performed by PDBS reduces the time of the hydrographic survey and the amount of time the crew spends on board, which is automatically reflected in the hydrographic survey's total cost.

Gordon J. (2011), in his article "*The Economic Benefits of Hydrography and Ocean Mapping*" [14], emphasizes the economic viability of hydrographic data. In addition, he indicates how updated hydrographic data can directly affect the strategic development of a particular area.

Douglas Connon B. and Nairn R. (2011), in the paper "*Economic Impact of Hydrographic Surveys*" [15], discuss the inherent values of hydrographic survey data and their apparent impact on nautical charts and navigation publications. They conclude that governments often give low priority to hydrographic surveys when allocating funds. They provide a detailed and reasoned insight into the benefits of up-to-date and reliable hydrographic survey data and draw attention to the fact that the survey is an essential element of the national structure and economic progress.

Genchi S. et al. (2020) in a paper *"Mapping topobathymetry in a shallow tidal environment using low-cost technology "* [16], Nikolakopoulos, K.G., et al. (2018) in the paper *"Synergistic use of UAV and USV dana and petrographic analyses for the investigation of beach rock formations: A case study from Syros Island, Aegean Sea, Greece "* [17], and Spect C. et al. (2020) in the paper *"Methodology for carrying out measurements of the tombolo geomorphic landform using unmanned aerial and surface vehicles near Sopot Pier, Poland"* [18] agree that use of more technologies reduces the cost of a hydrographic survey.

Poliyapram V. et al. (2017) in the paper *"Implementation of algorithm for satellite-derived bathymetry using open source GIS and evaluation for tsunami simulation"* [19], Duplačić Leder, T. et al (2019) in the paper *"Satellite Derived Bathymetry Survey Method – Example of Hramina Bay"* [20], and Duplančić Leder, T., Leder, N. (2020) in the paper *" Optimal conditions for satellite derived bathymetry (SDB) – case study of the Adriatic Sea"* [21] recognize that satellite can be used to increase survey coverage for shallow water (e.g., marine areas) that are not surveyed or areas with old bathymetric data.

Mateo-Perez V. et al. (2020) in the paper "*Port Bathymetry Mapping Using Support Vector Machine Technique and Sentinel-2 Satellite Imagery "* [22], Sagawa T. et al. (2019), in the article *"Satellite-Derived Bathymetry Using Machine Learning and Multi-Temporal Satellite Images"* [23], and Panagiotis A. et al. (2019) in the paper *"Shallow Water Bathymetry Mapping from UAV Imagery based on Machine Learning"* [24] have investigated the impact of new technologies and computational techniques such as artificial intelligence.

Le Deunf et al. (2020), in the paper *"A review of Data Cleaning Approaches in a Hydrographic Framework with a Focus on Bathymetric Multibeam Echosounder Datasets"* [25], conclude that none of the techniques is better than another but are more applicable to their native conditions of use.

According to the available literature, most scientists who study accuracy of hydrographic surveys give preference to instruments and processing from the data obtained in their research. It can be concluded that no one has used a complete approach in their research in reaching the optimal survey technique solution, especially with regards to the exact costs of the hydrographic survey. Therefore, a further scientific research needs to be conducted in this area.

1.4. Research methodology

For this doctoral dissertation, standard statistical metrics such as average value and collection coefficient, decision tree supervised learning method, multicriteria decision method, and reduced elimination matrix are used, including the available documentation, literature, data, already published results of research and the results of author's personal research. The analysis method, synthesis method, mathematical and statistical methods, and modelling methods are used in the process of conducting research and preparing this dissertation. Information, knowledge, and data obtained through literature and other sources, using the previously mentioned methods were cited to convey other observations, attitudes, conclusions, and knowledge in a scientifically based way. The databases and bibliographic references obtained via the Internet and other sources have been used to prepare the dissertation.

1.5. The structure of the thesis

The dissertation is organized into seven chapters. The introductory chapter is followed by Chapter 2, giving the basic characteristics of international hydrographic organizations, especially regarding the hydrographic survey. This chapter describes the importance, the fundamental goal, the objectives, and the mission of the IHO. The chronological overview of standards for conducting hydrographic surveys, and their recommendations concerning the category of the hydrographic survey, is transparently provided.

Chapter 3 addresses the analysis and evaluation of hydrographic surveys. The classification and analysis of the global state of the hydrographic survey by IHO regions are performed. The differences between the regions concerning coastline and sea surface are observed. So far, there is no data about that, the coastline length and sea surface are determined and calculated using the software Quantum Geographic Information System QGIS. Moreover, to understand how the survey coverage and the quality of the survey affect the safety of the navigation, a number of stranded ships are analysed through a ten-year period. The analysis is performed referencing the IHO regions, which also have not been investigated before.

In order to select the optimal hydrographic survey technology, it is necessary to classify and analyse the basic parameters in the function of the survey costs. According to this, in Chapter 4, the reciprocal cost ratio matrix of the hydrographic survey technologies was obtained and represented to emphasize cost difference. Furthermore, the parameters of the costs of hydrographic platforms and the parameters of the hydrographic survey area whose values can affect the cost are investigated.

Chapter 5 represents the novel methodology to select the optimal technology while maintaining the required level of the hydrographic survey quality. The model is based on the formulation of binary elimination matrix, a decision tree model is created, and Weighted Sum Model (WSM) as one optimization method is applied. The parameters that represent the input to the model are the reduced by binary elimination matrix and the optimization criteria. The binary matrix is obtained on the basis of available data of the survey area and available technologies. The binary values from the matrix are the basis for making a decision tree model. The optimization criteria are determined based on the financial budget, the time period available, and the desired level of accuracy. All mentioned elements in the matrix and the optimization criteria are filled by a hydrographer using the proposed methodology and available data. The so-called WSM score represents the output of the model. The mentioned score are numerical results which rank technologies for the hydrographic survey.

The application and validation of the proposed method are applied as a case study on Kaštela Bay, in Chapter 6. Based on the particular area data, a reduced binary elimination matrix is created. Based on the data from the elimination matrix, the decision tree model is proposed. For choosing the optimal technological solution, multi decision-making is performed by three criteria: cost, accuracy, and urgency. According to mentioned inputs in the proposed model, the optimal technologies' selection for Kaštela Bay is obtained as an output.

The results of the research, explanation of the scientific contribution, and the advantages of the proposed methodology are analysed in detailed in conclusion, in Chapter 7. Also, the limitations of the proposed methodology and future research directions are discussed.

2. BASIC CHARACTERISTICS OF INTERNATIONAL HYDROGRAPHIC ORGANIZATIONS AND HYDROGRAPHIC SURVEY

Hydrographic activity includes the research, collection of information, publishing, and data mapping on official nautical charts and navigation publications. The purpose of the hydrographic activity is to ensure safe navigation of vessels to protect human lives and property at sea, research, environmental protection, and marine management [2]. Hydrographic surveying is considered to be a part of the hydrographic activity. Its primary purpose is to collect hydrographic data that update nautical charts and navigation publications. It is carried out according to the standards prescribed by the International Hydrographic Organization [26], [27]. This chapter analyses the importance of International Hydrographic Organizations, its recommendations, and standards with particular reference to the hydrographic survey.

2.1. Recommendations and standards of the IHO

IHO performs numerous activities, including standardization, international maps, radio navigation warnings, digital databases and display, training, technical assistance, exchange of nautical charts and navigation publications, the establishment of regional hydrographic commissions, and issuance of publications. In order to perform these activities in the best possible way the IHO has so far developed international standards, specifications, and guidelines related to hydrography and the production of nautical charts and navigation publications. They are included in almost 60 IHO publications written primarily in English and French [28], [29].

The IHO Publications Catalogue contains a list and summary description of all publications. The publications are arranged according to classification criteria, in agreement with the Member States.

According to the agreed criteria, IHO publications are arranged under the following groups [28]:

- Bathymetric publications - mainly related to the General Bathymetric Chart of the Oceans (GEBCO);
- Capacity building publications - include technical topics and contributions to the IHO capacity building program;

- Periodicals - contain periodic events or refer to publications that, depending on their content, require periodic publication;
- Standards and specifications - refer to publications that contain standards, recommendations and guidelines, and
- Miscellaneous publications - publications that include general regulations and decisions and are most often of an administrative, informative or technical nature.

IHO standards and guidelines are developed and maintained by various IHO working groups. The groups are composed of representatives of the Member States with appropriate skills, knowledge, and experience. In most cases, especially when it comes to technical standards, the working groups also include representatives from the Non-Governmental International Organizations (NGIO) and invited expert associates.

They mainly come from related industries, and their practical experience is of great importance in proposing new standards or in substantial revisions of existing standards. Before entry into force, standards should be approved by most IHO Member States [30].

The Hydrographic Surveys Standards (IHO Standards for Hydrographic Surveys S-44) are a set of minimum requirements that need to be met to achieve the desired level of hydrographic survey accuracy. The standards classify the areas of hydrographic survey, accuracy, depth of measurement, degree of seabed exploration, size of obstacles that must be detected, and accuracy of position during hydrographic survey [31].

Although the International Hydrographic Organization is exclusively advisory and technical, it has a vital role in standardization, development, and guidance in hydrographic activity. IHO standards regulate only technical issues, but data collected under these standards directly affect the accuracy of product data of hydrographic organizations.

2.2. Evaluation of recommended methods in hydrographic survey categories

The hydrographic survey is carried out according to the IHO publication Standards for Hydrographic Survey (S-44). The IHO began proposing standards for hydrographic surveys during the 1957 International Hydrographic Conference. Until now, six editions of standards for conducting hydrographic surveys are known. The chronological overview of hydrographic survey standards is represented according to [32] in Table 2.

Table 2.1 Chronological overview of standards for conducting hydrographic surveys

Number, year and edition name	General Recommendations	Special recommendations
Edition 1, 1968. "Accuracy Standards Recommended for Hydrographic Surveys "	The study was limited to determining the density and accuracy of measurements required to display the seabed and other features, which must be sufficiently accurate for navigational purposes.	Maximum acceptable depth measurement error: • 0.3 m for depth 0 - 20 m • 1 m for depth 20 - 100 m • 1 % for depth > 100 m
Edition 2, 1982. "IHO Standards for Hydrographic Surveys and Classification Criteria for Deep Sea Soundings "	The study tightened the required accuracy when measuring depths due to the increasing draft of ships and for the purpose of safer navigation.	Maximum acceptable depth measurement error: • 0.3 m for depth 0 - 30 m • 1 m for depth 30 - 100 m • 1 % for depth > 100 m
Edition 3, 1987. "IHO Standards for Hydrographic Surveys, Classification Criteria for Deep Sea Soundings and Procedures for Elimination of Doubtful Data "	The need for the introduction of hydrographic equipment that covers the entire seabed in the recommended areas was identified.	Maximum acceptable depth measurement error: • 0.3 m for depth 0 - 30 m • 1 % for depth > 30 m
Edition 4, 1998. "Standards for Hydrographic Surveys "	Four categories of the hydrographic survey were defined, full seabed coverage was recommended in the area of the special category (critical area below the keel) and in the area of category 1 (ports, access to ports, docks, etc.).	Permissible positioning and depth measurement errors were defined.

Edition 5, 2008. "Standards for Hydrographic Surveys "	Compared to the previous edition, the first category was divided into the first category a (where is a complete seabed search was required) and the first category b (where a complete seabed search was not required) and the third category was abolished.	Clear guidance regarding seafloor features and uncertainty are defined. In addition, a minimum spot spacing for LIDAR was included for Order 1b surveys where full seafloor search is not required.
Edition 6, 2020. "IHO Standards for Hydrographic Surveys "	In this edition, five orders of the hydrographic survey were defined. A more stringent Exclusive Order was introduced.	The minimum standards required achieving each Order along with a new tool for enhancing and customizing these orders was set.

From Table 2.1, it can be seen that until the fourth edition of the IHO Standard for Hydrographic Survey from 1998 the categories in which the measurement is carried out have not been defined. However, according to the IHO publication S-44 from 2020, which is in force today, five orders were defined in which hydrographic survey is to be carried out, as shown in Figure 2.1.

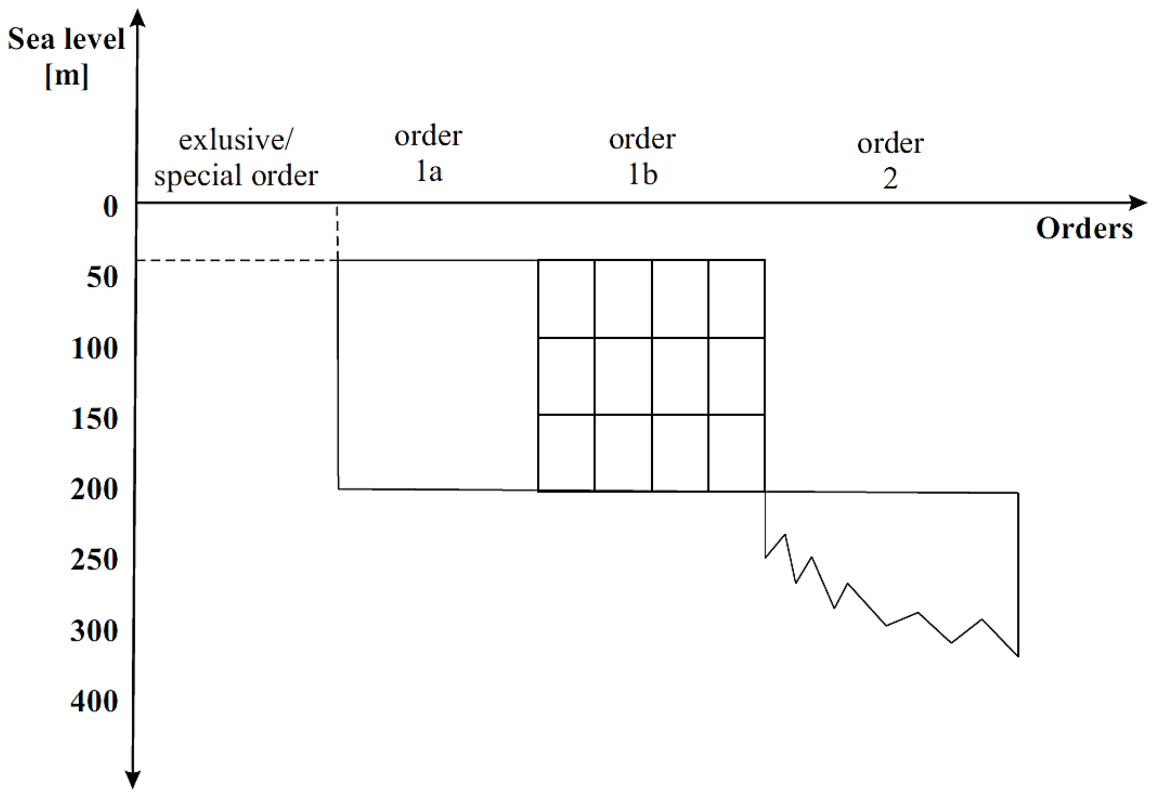


Figure 2.1 Model of hydrographic survey categories

Exclusive Order hydrographic surveys are an extension of the IHO Special Order with more stringent uncertainty and data coverage requirements. Their use is intended to be restricted to shallow water areas (harbours, berthing areas, and critical areas of fairways and channels) where there is an exceptional and optimal use of the water column and where specific critical areas with minimum underkeel clearance and bottom characteristics are potentially hazardous to vessels. For this Order, a 200 % feature search[1] and a 200 % bathymetric coverage[2] are required. The size of features to be detected is deliberately more demanding than for Special Order [32].

A special order is intended for those areas where under keel clearance is critical. Therefore, 100 %[3] feature search and 100 %[4] bathymetric coverage are required. Examples of areas that may require Special Order surveys are berthing areas, harbours, and critical areas of fairways and shipping channels [32].

Order 1a is intended for areas where features on the bottom may become a concern for the type of surface traffic expected to transit the area but where the underkeel clearance is considered not to be critical. A 100 % feature search is required to detect features of a specified size. The bathymetric coverage less than or equal to 100 % is appropriate as long as the least depths over all significant features are obtained and the bathymetry provides an adequate depiction of the nature of the bottom topography. Underkeel clearance becomes less critical as depth increases, so the size of the feature to be detected increases with depth in areas where the water depth is greater than 40 metres. The examples of areas that may require Order 1a surveys are coastal waters, harbours, berthing areas, fairways and channels [32].

Order 1b is intended for areas where the types of surface vessels expected to transit the area are such that a general depiction of the bottom is considered adequate. As a minimum, an evenly distributed bathymetric coverage of 5 % is required for the survey area.

[1] 200 % feature search may be accomplished by adequately overlapping collection or by acquiring more than one independent dataset within a survey [32].

[2] Greater than 100 % bathymetric coverage, including 200 % for Exclusive Order, may be accomplished by adequately overlapping collection or by acquiring more than one independent dataset within a survey [32].

[3] A 100 % feature search may be achieved with a survey system that does not measure depth. Under those circumstances, least depth measurements from an independent bathymetric system will be required for any detected significant feature. Whenever possible, it is recommended to conduct a 100 % feature search in conjunction with 100 % bathymetric coverage [32].

[4] A 100 % bathymetric coverage should be interpreted as “full” bathymetric coverage. 100 % bathymetric coverage does not guarantee continuous depth measurements, since the depth measurements are discrete and based on the inherent physical and survey instrumentation limitations [32].

This means that some features will not be detected, although the distance between bathymetric coverage areas will limit the size of those features. This Order of survey is only recommended where underkeel clearance is considered not to be an issue. An example would be an area where the bottom characteristics are such that the likelihood of a feature on the bottom that will endanger the type of surface vessel expected to navigate the area is low [32].

Order 2 is the least stringent Order and is intended for areas where the depth of water is such that a general depiction of the bottom is considered adequate. As a minimum, an evenly distributed bathymetric coverage of 5 % is required for the survey area. It is recommended that Order 2 surveys are conducted in areas that are deeper than 200 m. Once the water depth exceeds 200 m, the existence of large enough features to impact surface navigation and yet remain undetected by an Order 2 survey is considered unlikely [32].

In addition to the prescribed recommendations, the IHO Standards for Hydrographic Surveys defines minimum bathymetry standards for the safety of navigation surveys. According to [32], a diagram of minimum bathymetry standards regarding Orders is done and shown in Figure 2.2.

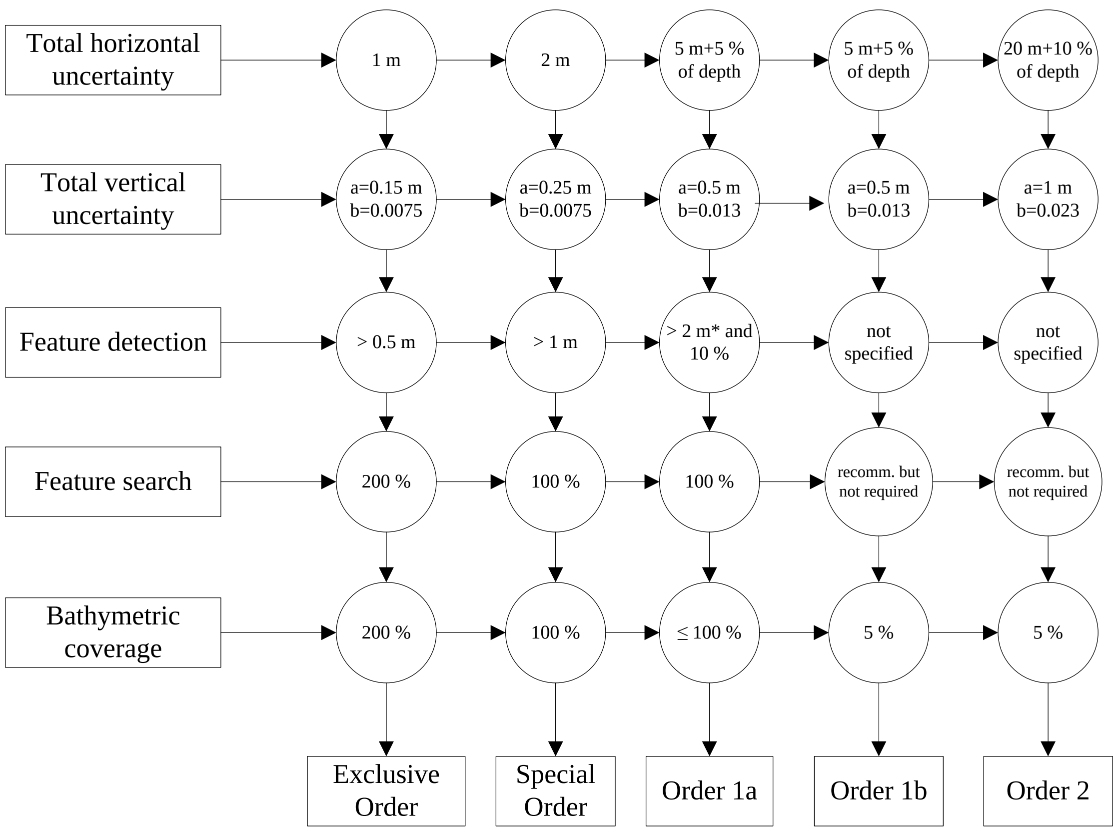


Figure 2.2 Diagram of Minimum Bathymetry Standards for Safety of Navigation Hydrographic Survey

Considering Figure 2.2, five different survey orders are defined, and minimum requirements for hydrographic survey vary with water depth, geophysical properties, and expected shipping types.

Minimum requirements include [32]:

- Total horizontal uncertainty (THU) - Component of total propagated uncertainty (TPU)[5] calculated in the horizontal dimension. THU of the measured depths is 1 m for Exclusive Order and 2 m for Special Order areas. In other orders, it also depends on the depth of the survey area.
- Total vertical uncertainty (TVU) - Component of total propagated uncertainty (TPU) calculated in the vertical dimension. The maximum allowable total vertical error is calculated by the following expression (2.1) [33]:

$$\pm\sqrt{a^2 + (b \cdot d)^2} \tag{2.1}$$

  Where a - is a part of error that does not vary with depth, b - is coefficient representing the part of error that varies with depth, d - is depth, $(b \cdot d)$ - a part of the error that varies with depth.
- Feature detection – Ability of a system to detect features of a defined size. A cubic feature is a basic shape reference for system feature detection ability and implies a symmetrical 3D shape of six equal square sides. For the Exclusive and Special Order, minimum requirements for feature detection are defined for > 0.5 m, and > 1 m. For Order 1a, the requirements are defined as cubic features > 2 m in the depths of 40 m and 10 % of depth beyond 40 m. For Order 1b and Order 2, the requirements are not specified so that the surface navigation is not compromised [32].
- Feature search – Extent to which an area is surveyed using a systematic method of identifying features [32]. The feature search is rigorously defined for the Exclusive Order, Special Order, and Order 1a. For Order 1b and Order 2, the feature search is recommended but not required by the minimum standard for hydrographic survey.
- Bathymetric coverage - Acquisition of bathymetric coverage requires the use of a sensor that measures and records depths. The minimum bathymetric coverage to be achieved by each survey order is defined by IHO Standard S-44. In addition, the system-independent parameter bathymetric coverage expressed in percentage is used for all Orders [32].

[5] Three dimensional uncertainty with all contributing measurement uncertainties included [32].

The standards are intended to be purpose-specific but technology-independent in design. The minimum navigational aid, structural and topographic positioning standards for the safety of navigation surveys above the vertical datum are also included in IHO Standards for Hydrographic Surveys. The Order achieved for bathymetry data may be assessed independently of the Order performed for other positioning data. These standards only apply where such measurements are required for the survey. Other minimum standards for the safety of navigation surveys are represented in Table 2.2, which is made according to [32].

Table 2.2 Other Minimum Standards for Safety of Navigation Survey

Other requirements for the hydrographic survey Orders	**Marks**	**Meaning**
Allowable THU for positioning fixed objects, aids, features above the vertical reference significant to navigation[6]	f_{h1}	Recommendation for Exclusive Order is 1 m
	f_{h2}	Recommendation for Special Order, Order 1a, and Order 1b is 2 m
	f_{h3}	Recommendation for Order 2 is 5 m
Allowable TVU for positioning fixed objects, aids, features above the vertical reference significant to navigation	f_{v1}	Recommendation for Exclusive Order is 0.25 m
	f_{v2}	Recommendation for Special Order is 0.5 m
	f_{v3}	Recommendation for Order 1a is 1 m
	f_{v4}	Recommendation for Order 1b and Order 2 is 2 m
Floating objects and aids to navigation[7]	n_1	Recommendation for Exclusive Order is 5 m
	n_2	Recommendation for Special Order, Order 1a, and Order 1b is 10 m
	n_3	Recommendation for Order 2 is 20 m
Coastline[8]	c_1	Recommendation for Exclusive Order is 5 m
	c_2	Recommendation for Special Order, Order 1a, Order 1b and Order 2 is 10 m

[6] Fixed aids to navigation include beacons, day marks, range marks and lighthouse [32].
[7] Floating objects and aids to navigation include, but are not limited to buoys, articulated beacons, fish farms and floating docks. Allowable THU for the positioning of these objects are presented in Table 2.2. Allowable TVU is not applicable to these measurements [32].
[8] Coastline is the line where shore and water meet, more specifically can be described as high water mark, or the line of mean water level where there is no appreciable tide or charge in water level [34]. Allowable TVU is not applied to these measuremenet within this standard, so only allowable THU is presented in table 2.2 [32].

Allowable THU for positioning features above the vertical reference less significant to navigation[9]	v_{h1}	Recommendation for Exclusive Order is 2 m
	v_{h2}	Recommendation for Special Order is 10 m
	v_{h3}	Recommendation for Order 1a, Order 1b, and Order 2 is 20 m
Allowable TVU for positioning features above the vertical reference less significant to navigation	v_{v1}	Recommendation for Exclusive Order is 0.3 m
	v_{v2}	Recommendation for Special Order is 0.5 m
	v_{v3}	Recommendation for Order 1a is 1 m
	v_{v4}	Recommendation for Order 1b is 2 m
	v_{v5}	Recommendation for Order 2 is 3 m
Allowable THU for positioning of overhead clearances and range line, sector line heights[10]	o_{h1}	Recommendation for Exclusive Order is 1 m
	o_{h2}	Recommendation for Special Order is 2 m
	o_{h3}	Recommendation for Order 1a is 5 m
	o_{h4}	Recommendation for Order 1b and Order 2 is 10 m
Allowable TVU for positioning of overhead clearances and range line, sector light heights	o_{v1}	Recommendation for Exclusive Order is 0.3 m
	o_{v2}	Recommendation for Special Order is 0.5 m
	o_{v3}	Recommendation for Order 1a is 1 m
	o_{v4}	Recommendation for Order 1b is 2 m
	o_{v5}	Recommendation for Order 2 is 3 m

Considering all the recommendations for hydrographic surveys, in Table 2.2, for performing hydrographic surveys, it is proposed to investigate their relationship between the categories. Figure 2.3 shows the relationships of the recommendations between the Orders of hydrographic surveys, including the differences and overlap of these recommendations' independence on the hydrographic surveys' Order of performance.

[9] Features less significant to navigation are nonconspicuous features which provide context and additional information, but are not likely to aid navigation. Topographic features less significant to navigation may include, but are not limited to nonconspicuous landmarks such as chimneys, flare stacks, hill or mountain tops, masts, monuments, towers, refineries, religious buildings, silos, single buildings, tanks, tank farms and windmills [32].

[10] Overhead obstructions such as bridges and cables may pose a hazard to navigation. Range line and sector light heights may be of use for determining distance from shore. Allowable THU and TVU for the positioning of overhead clearances (including associated horizontal clearances), range line and sector light heights are presented in Table 2.2. [32].

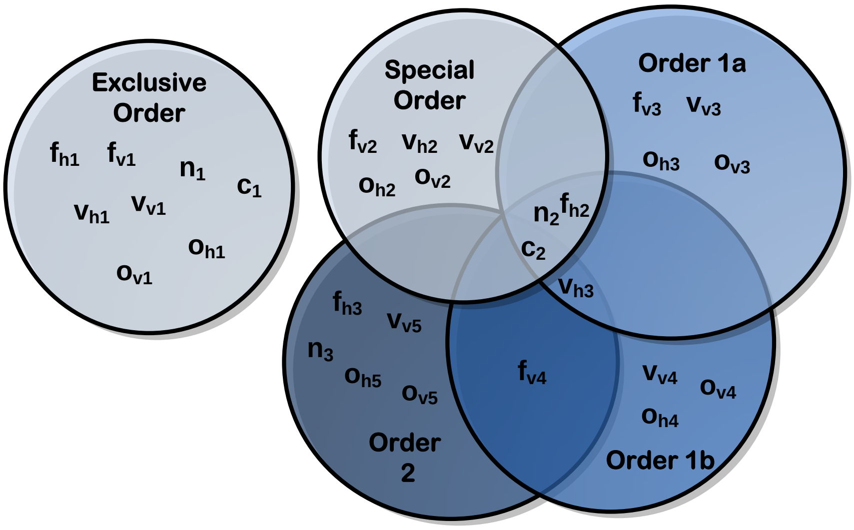


Figure 2.3 Relationship of recommendations in hydrographic survey Orders

The recommendations in Orders of hydrographic surveys, shown by a developed model in Figure 2.3, can be represented as sets of elements, expression (2.2), (2.3), (2.4), (2.5) and (2.6):

$$E_0 = \{f_{h1}, f_{v1}, n_1, c_1, v_{h1}, v_{v1}, o_{h1}, o_{v1}\} \quad (2.2)$$

$$S_0 = \{f_{h2}, f_{v2}, n_2, c_2, v_{h2}, v_{v2}, o_{h2}, o_{v2}\} \quad (2.3)$$

$$O_{1a} = \{f_{h2}, f_{v3}, n_2, c_2, v_{h3}, v_{v3}, o_{h3}, o_{v3}\} \quad (2.4)$$

$$O_{1b} = \{f_{h2}, f_{v4}, n_2, c_2, v_{h3}, v_{v4}, o_{h4}, o_{v4}\} \quad (2.5)$$

$$O_2 = \{f_{h3}, f_{v4}, n_3, c_2, v_{h3}, v_{v5}, o_{h5}, o_{v5}\} \quad (2.6)$$

where E_o - is a set of elements of an Exclusive Order, S_o - is a set of elements of Special Order, O_{1a} - is a set of elements of Order 1a, O_{1b} - is a set of elements of Order 1b, O_2 - is a set of elements of Order 2.

Mathematical operations with sets can show the differences in recommendations between the Orders of a hydrographic survey. The set of all elements are elements of set A but not elements of set B, and this is called the difference of sets A and B, expression (2.7) [18]:

$$A \setminus B = \{x | x \in A \wedge x \notin B\} \quad (2.7)$$

Considering all Orders of the hydrographic survey except Exclusive Orders, the most significant differences in recommendations were observed between Special Order and Order 2 and between Order 1a and Order 2, expressions (2.8), (2.9):

$$S_o \;/\; O_2 = \{f_{h2}, f_{v2}, n_2, v_{h2}, v_{v2}, o_{h2}, o_{v2}\} \tag{2.8}$$

$$O_{1a} \;/\; O_2 = \{f_{h2}, f_{v3}, n_2, v_{v3}, o_{h3}, o_{v3}\} \tag{2.9}$$

From the analysis conducted in the chapter, the following can be concluded: Hydrographic data are responsible for accurate nautical charts and publications. The adequate and up-to-date hydrographic data represent the security foundations for safety at sea. Based on the chronological overview of hydrographic survey standards and other recommendations with respect to the Orders of hydrographic survey, transparent analysis and introduction have been developed. It is clear that IHO recognizes the need for standards and recommendations to be more rigorous, especially in exclusive order where the possibility of stranding is increased. The questions arise as to how this is reflected on coverage of hydrographic surveys by the IHO regions worldwide. Hence, an interconnection between the stranded ships and an adequate surveyed area up to 200 m by the IHO regions has to be noted. Furthermore, since there is a connection between the stranded ships and an adequate surveyed area, the next chapter will analyse and evaluate the implementation of hydrographic surveys by IHO regions and the impact of hydrographic surveys on navigation safety regarding stranding over ten years.

3. ANALYSIS AND EVALUATION OF HYDROGRAPHIC SURVEYS

The International Hydrographic Organization is constantly working to achieve maximum standardization of nautical charts and navigation publications and services and hydrographic surveying practices. Nevertheless, there are no indications for a significant improvement in the level of implementation of hydrographic surveys in the world. This chapter identifies some disparities between IHO regions. Since previous research paid no attention to the calculation of the coastline and the sea surface by region, such analysis has become a subject of interest. Moreover, to understand how the survey coverage and the quality of surveys affect navigation safety, the number of stranded ships was analysed by IHO regions through a ten-year data period.

3.1. Coverage of hydrographic surveys in the world

The International Hydrographic Organization identifies priorities requiring cooperation and assistance to improve navigation safety and the protection of the marine environment through adequate hydrographic surveys. Despite all the efforts of the IHO to improve the state of implementation of hydrographic surveys in the world, the problem of accuracy and coverage of the survey still exists.

The SOLAS Convention gives a direct and precise obligation for the functioning of hydrographic activities. In Chapter V, Regulation 9 of the SOLAS Convention, Contracting Governments must ensure [35], [36]:

- Performing hydrographic changes and publishing data on nautical charts and manuals;
- The greatest possible uniformity of nautical charts and navigational publications considering relevant international recommendations and
- Coordination of its activities to ensure the timely availability of Maritime Safety Information - MSI.

In 1970, the United Nations began evaluating the current state and progress in hydrographic surveys around the world. As a part of the evaluation process, the IHO undertook a detailed study during the 1980s based on a series of questionnaires issued to coastal states. The analysed data were presented in the IHO publication "C-55 Status of hydrographic surveying and nautical charting".

In the first edition of the IHO C-55 (S-55) publication from 1991, the represented data covered 46 % of the world's coastal states. The purpose of C-55 publication is to provide a database that assists governments and international organizations in the best implementing implementation of the obligations set out in Chapter V, Regulation 9 of the SOLAS Convention [37]. The second edition of C-55 (S-55) publication was issued by the IHO in 1998, based on the collected data in the period from 1995 to 1996. The analysed and presented data covered 47 % of the coastal states of the world, only 1 % more than the previous edition [37]. The third edition has been in force since 2004. The aims of the third edition are to present a clear picture of the coverage of world waters by hydrographic surveys and the extent of the effectiveness of organizations to publish information relevant to navigation safety in a timely manner. The publication was supervised by the IHO Capacity Building Subcommittee (CBSC) in collaboration with the Regional Hydrographic Commissions [37].

Nowadays, the content of the publication is maintained on the IHO website and includes data for 90 % of the world's coastal states. The most significant gaps, where data are not available for analysis, are found in the Central American, Mediterranean, and Black Sea regions, parts of the Indian Ocean and neighbouring seas, and the southern China Sea and adjacent straits and seas [37]. The status of coverage of world waters by hydrographic surveys at sea depths below and above 200 m is made according to [37] as shown in Figure 3.1.

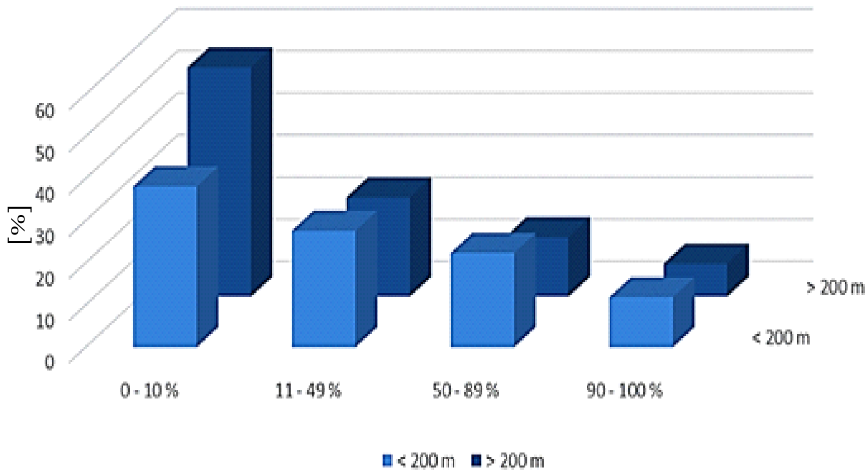


Figure 3.1 The status of implementation of the adequate hydrographic survey in world seas

Considering Figure 3.1, at depths up to 200 m, it was concluded that out of the total number of seas listed in the C-55 publication, just about 10 % of them performed an adequate hydrographic survey in the scope of 90 – 100 %. Thus, almost 40 % of seas listed within C-55 as adequate hydrographic surveyed seas have more than 90 % of their territory unsurvey. At depths > 200 m, almost 50 % of the total numbers of adequate hydrographic surveyed seas are performed on a maximum of 10 % surveyed territory. Thus, less than 10 % of the total number has conducted an adequate hydrographic survey in the range of 90 – 100 %. A state of the hydrographic survey by IHO regions at depth up to 200 m is made according to [37], as shown in Figure 3.2.

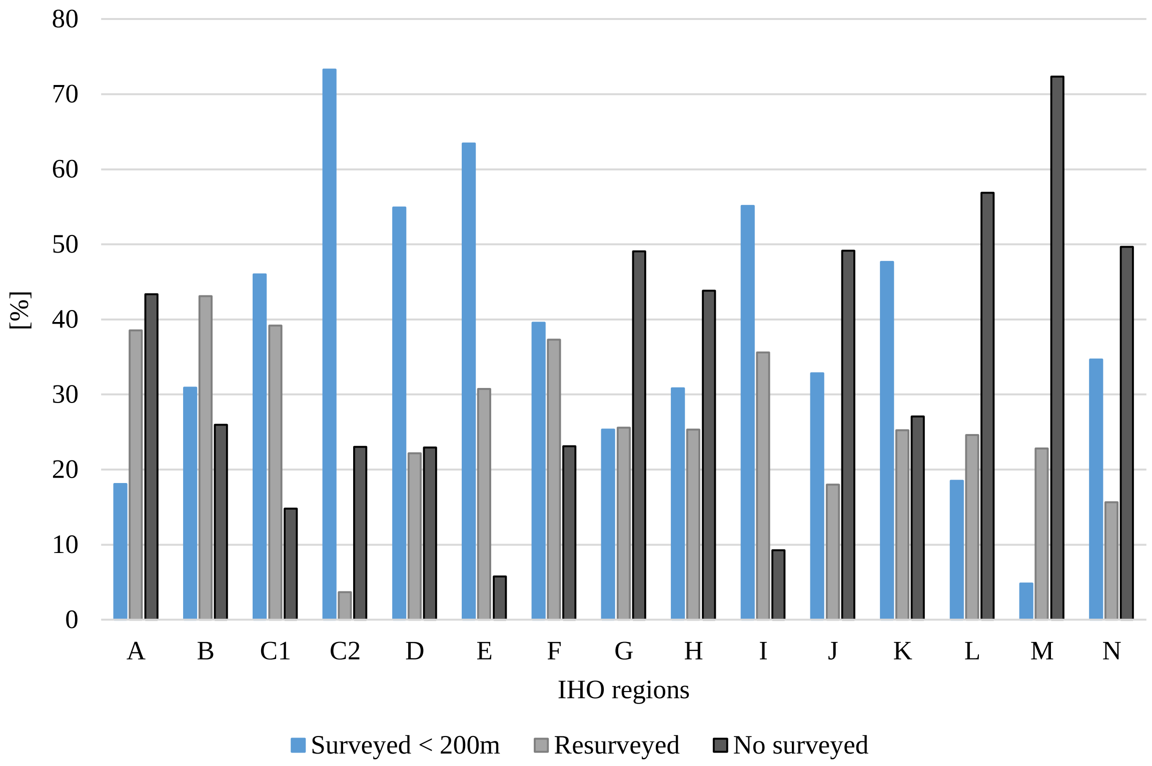


Figure 3.2 State of the hydrographic survey by IHO regions at depths up to 200 m

According to Figure 3.2, the state of adequate hydrographic survey exceeding 50 % of the total waters is evident only in regions C2, D, E, and I. The region where it is necessary to repeat the hydrographic survey, in more than 40 % of the total waters, is the hydrographic region B. In the hydrographic regions A, G, H, J, L, M, and N, more than 40 % of the water surface at depths up to 200 m is not surveyed. By observing the ratio of the unsurvey area, it is concluded that the worst situation is in the hydrographic region M.

According to statistical data, in the last ten years, the melting of ice and an increase in temporal availability of the area has increased the volume of maritime traffic in the Arctic [37]. This data precisely indicates the importance of including adequate hydrographic measurements in navigation safety. The increase in marine traffic using unreliable nautical charts and navigation publications increases potential maritime accidents. Furthermore, the state of the hydrographic survey at depths greater than 200 m is analysed according to [37] as shown in Figure 3.3.

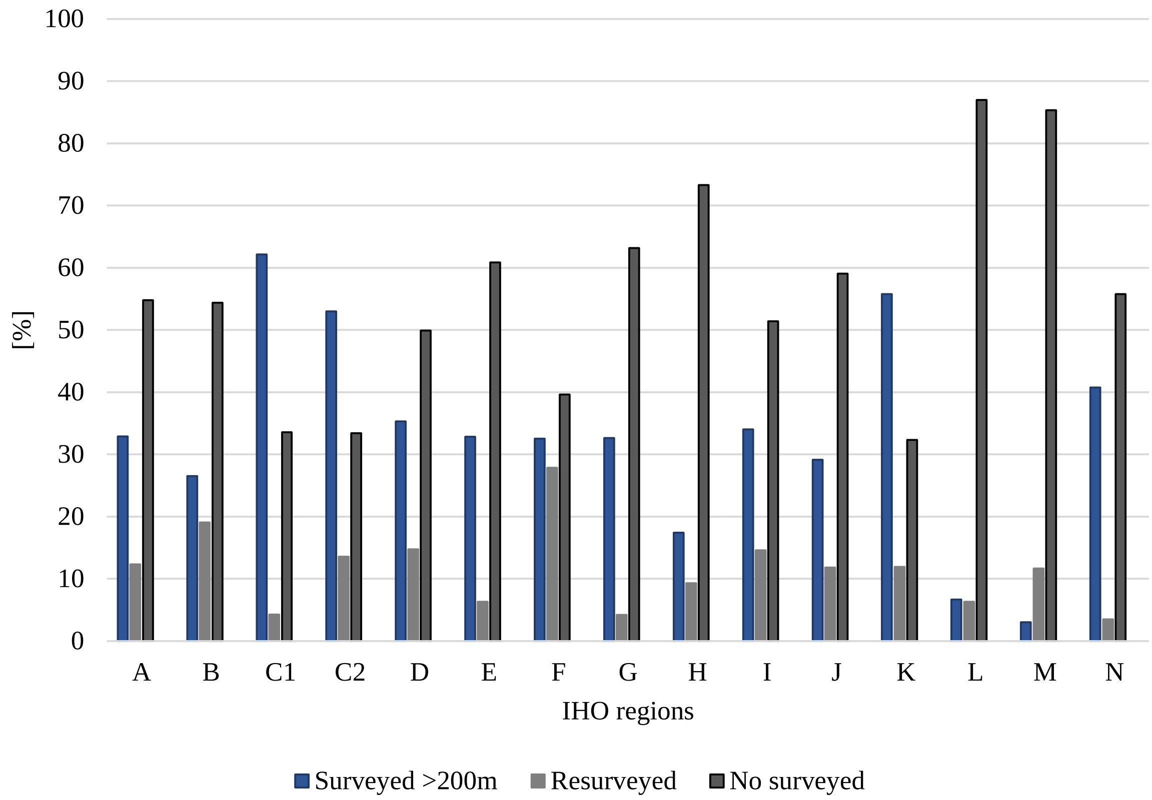


Figure 3.3 State of the hydrographic survey by IHO regions at depths greater than 200 m

Considering Figure 3.3, it was concluded that adequate hydrographic survey is conducted in the range greater than 50 % of total waters, only in hydrographic regions C1, C2, and K. Hydrographic regions in which more than 50 % of the sea is not surveyed at all are A, B, E, G, H, I, J, L, M and N. In three of these regions, the percentage of no surveyed waters exceeds 80 % and this refers to regions H, L, and M.

An assumption about the possible new and unexplored parameters that could help identify risk regions in existing hydrographic surveys was made. The coastline length and sea surface were identified as novel parameters. To confirm the assumption, calculation of these parameters for all IHO regions was made, and these parameters were compared with extracted data from the hydrographic survey. Also, calculations have been performed using QGIS. It is an Open Source Geographic Information System (GIS) licensed under the GNU General Public License. QGIS is an official project of the Open Source Geospatial Foundation [38]. A general framework for QGIS is proposed in Figure 3.4.

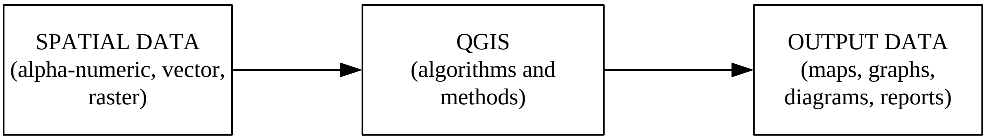


Figure 3.4 A general framework for QGIS

QGIS has a built-in function and algorithms to calculate various properties based on the feature geometry, such as line length and area. For example, the coastline length and sea surface calculation are made according to the model shown in Figure 3.5.

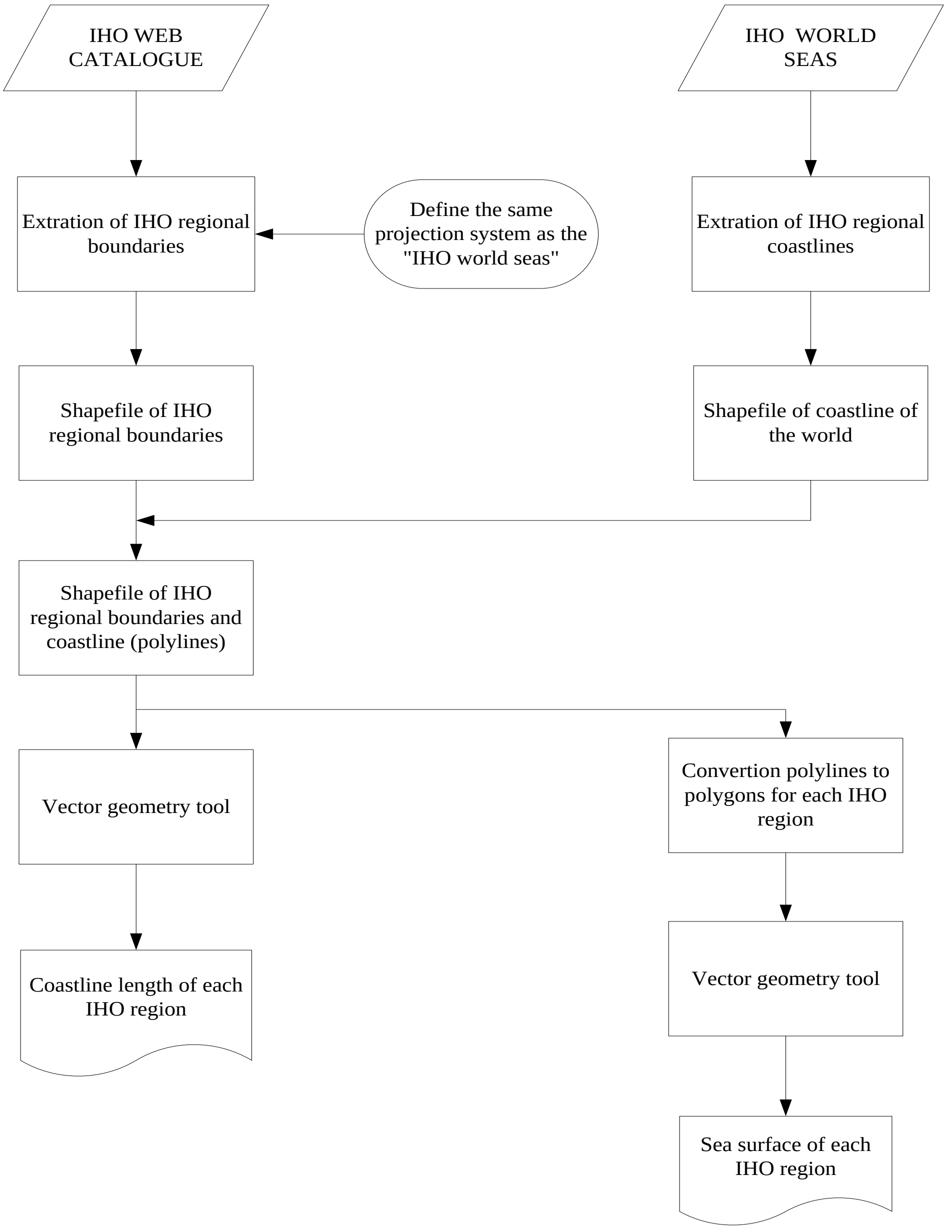


Figure 3.5 Model for calculating coastline length and sea surface by IHO region using QGIS

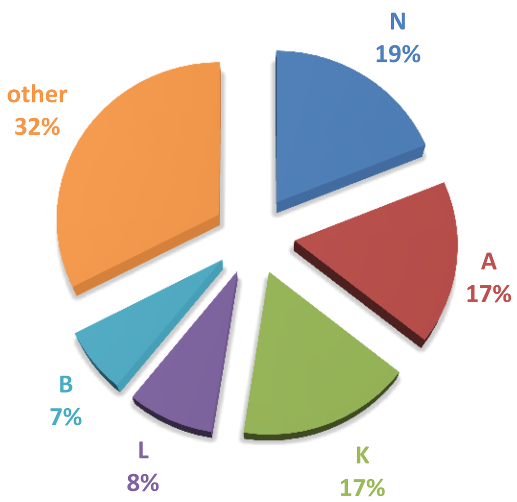
According to Figure 3.5, existing data from "IHO web catalogue" and "IHO world seas", a chart provided by IHO and available for download as a shapefile on IHO official website [1], were used to the extraction of IHO boundaries. Georeferencing requires using QGIS software that can assign new coordinates to the shapefile by applying a geometric transformation.

Extraction of IHO coastline was performed from "IHO world seas". Since polygons represent the seas, converting the polygons into lines to get the coastline shape line was necessary. The boundaries of IHO regions and IHO coastlines were made and extracted in the new shapefiles to the reference input data. The new shapefiles were created for each feature: the points, polylines, and polygons, and they needed to be georeferenced to the reference data. The coastline length of each IHO region was obtained using a vector geometry tool to reference input data. The polylines within boundaries of IHO regions that correspond to the coastline of the region were calculated for length using QGIS vector geometry tool. From the gained boundaries, the polygons of IHO regions were made, and the surface of these polygons that corresponds to the sea surface of a given region was calculated using vector geometry algorithms embedded in QGIS tools. The obtained results by IHO regions are represented in the Table 3.1.

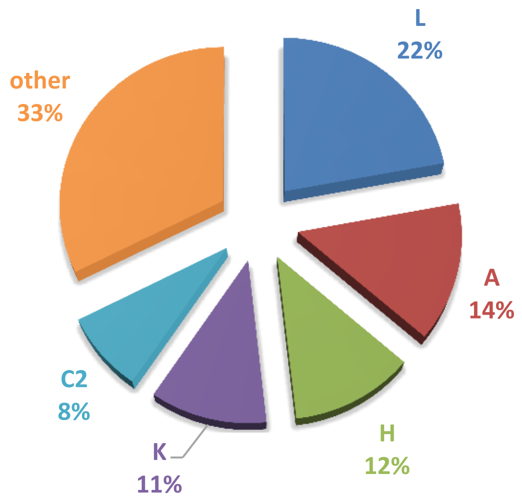
Table 3.1 The investigated relevant parameters by IHO regions

Regions	**Coastline length [M]**	**Sea area [km²]**
A	179.875	51.227.091.12
B	71.012	17.593.214.02
C1	33.285	18.347.282.55
C2	49.303	29.173.572.08
D	56.478	5.394.984.57
E	34.170	410.040.85
F	33.696	2.986.455.38
G	30.830	14.776.171.57
H	24.052	43.040.129.87
I	11.734	1.050.337.55
J	46.379	22.245.978.78
K	179.220	40.773.776.15
L	89.256	79.721.336.39
M	29.519	21.633.826.45
N	202.414	12.464.950.13

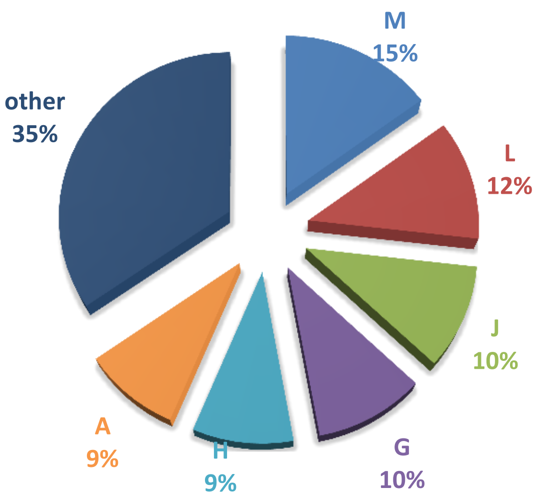
For a more precise analysis of the relationship of the investigated parameters, Figure 3.6 shows the data related to the highest values of individual parameters depending on the IHO regions.



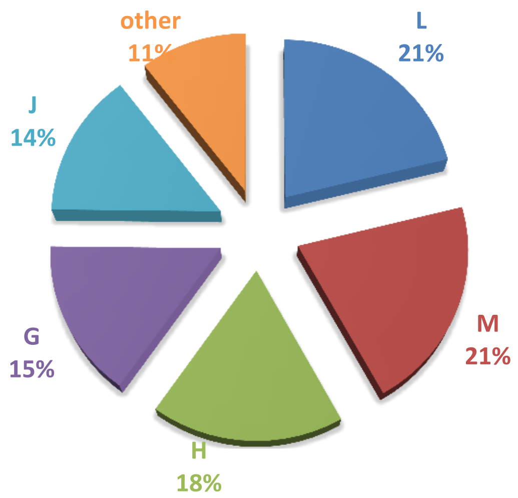
(a)



(b)



(c)



(d)

Figure 3.6 The relationship of the investigated parameters by IHO regions: (a) Coastline length by IHO regions; (b) Sea surface by IHO regions; (c) No surveyed areas at depth < 200 m; (d) No surveyed areas at depth > 200 m

According to the Figure 3.6 (a) it was concluded that more than 60 % of the world's sea coastline belongs to four regions N, A, K and L. In terms of the sea surface areas, according to Figure 3.6 (b), almost 60 % belong to four regions L, A, H and K, out of which region L encompasses even 22 % of the total surface. Considering no surveyed areas by IHO regions, it is evident that region L has the highest percentage of no surveyed areas, 12 % at depths up to 200 m according to the Figure 3.6 (c) and 21 % at depths greater than 200 m, as shown in figure 3.6 (d).

Comparing the coastline length represented in Figure 3.6 (a) with the number of members by IHO regions, it is concluded that regions A and N have the longest coastline and have among the smallest number of Member States. Observing non surveyed areas by IHO regions, the relation between a small number of Member States and a high percentage of no surveyed areas is evident.

The information provided in C-55 is not entirely accurate since it is left to each state to determine how to use data to estimate percentages of adequate survey coverage. Therefore, it is justifiably considered that the state of coverage by adequate measurement covers a smaller area than it is shown by the analysis in this dissertation. Such an analysis provides a global picture of the implementation of hydrographic surveys by IHO regions.

It can be assumed that the current data indicates the need to improve the level of implementation of hydrographic surveys significantly.

Because of the above, it is proposed to investigate their mutual influence on the coverage of the adequate hydrographic survey. Therefore, Figure 3.7, made according to [37], shows the relationships of adequate hydrographic survey, coastlines length, and sea surface by IHO regions.

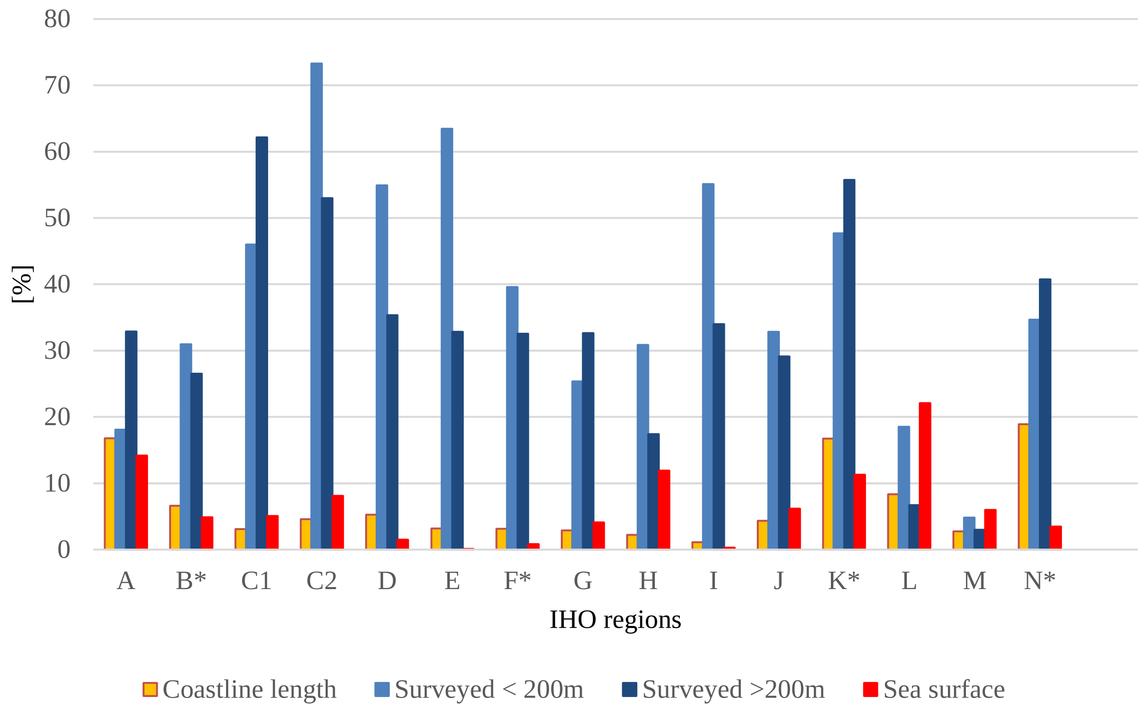


Figure 3.7 Relationship between coastline length and sea surface by IHO regions with respect surveyed areas and number of Member States

According to Figure 3.7, generally, the adequate hydrographic survey coverage is inversely proportional to the coastline length, and sea surface area by IHO region. The exceptions to this claim are B, F, K, and N regions whose data are missing from IHO publication C-55.

3.2. The impact of hydrographic surveys on navigation safety

The importance of hydrographic surveying refers to obtaining exact data to make nautical charts and navigation publications with special emphasis on the possibilities that may affect the safety of navigation. In the last few decades, the need for adequate coverage of hydrographic surveys and the production of nautical charts and navigation publications according to the SOLAS Convention requirements in Chapter V has increased [39].

Important factors that have an influence on this are:

- An increasing number of VLCCs with an extremely large draft;
- The need to protect the marine environment;
- Change in maritime trade patterns and
- The growing importance of the seabed resources.

More than 80 % of international world trade is conducted by sea [40], [41]. A large percentage of the world's seas, straits, and ports do not have adequate nautical chart coverage. Navigation charts are essential tools for marine navigation. Most charts contain a mixture of surveys of different quality [42]. They rely on data when hydrographic survey methods have been limited. Many nautical charts that were accurate and reliable in previous years do not represent the real situation today. They are incomplete and inaccurate [3], [43].

Today the savings in funds and sailing time result in the use of shorter routes and the possibility of using larger ships, therefore the safety of navigation largely depends on the existence, coverage, and availability of accurate and up-to-date hydrographic data. Lack of relevant hydrographic survey information can lead to maritime casualties and incidents and hinder maritime trade development [44].

Maritime casualties and incidents are often the results of several factors, and it is extremely difficult to conclude whether this situation is caused solely by inadequate hydrographic data. It can be concluded that incomplete and inaccurate hydrographic data are one of the significant causes of the maritime accident that can result in the shipwreck. Therefore, this paper analyses the data on stranded ships, available from [45], in the period from 2009 to 2019. The final results were obtained using standard statistical metrics are shown in Figure 3.8.

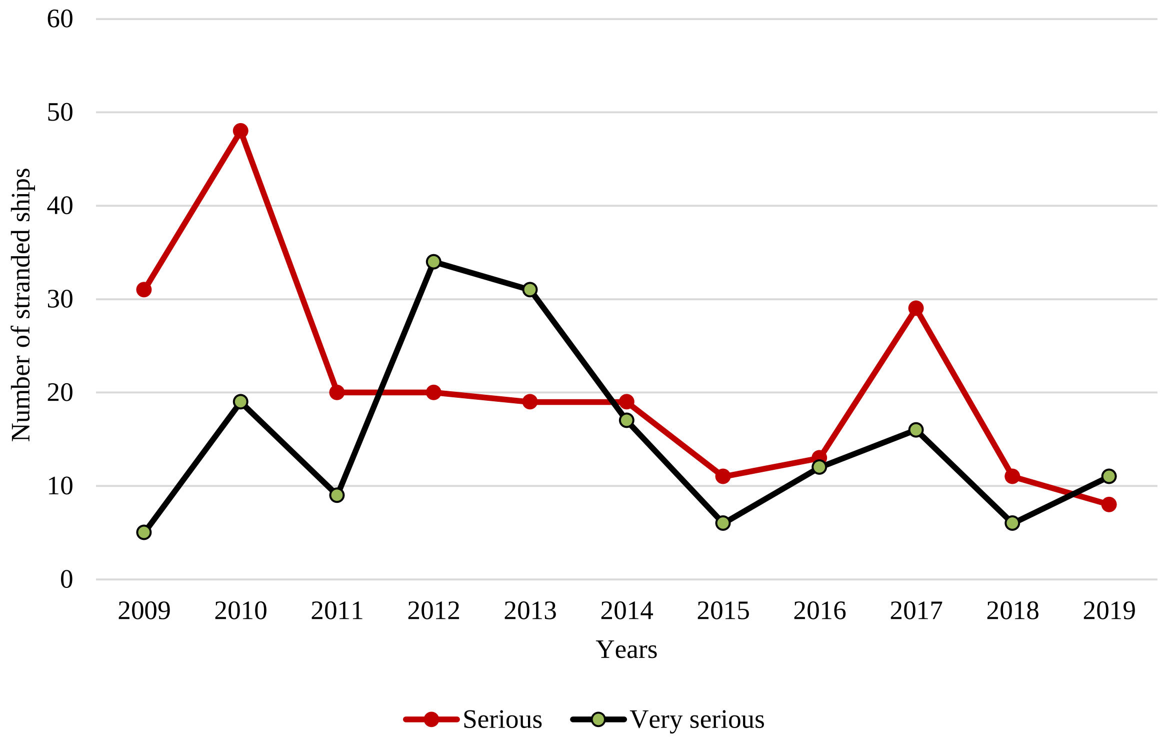
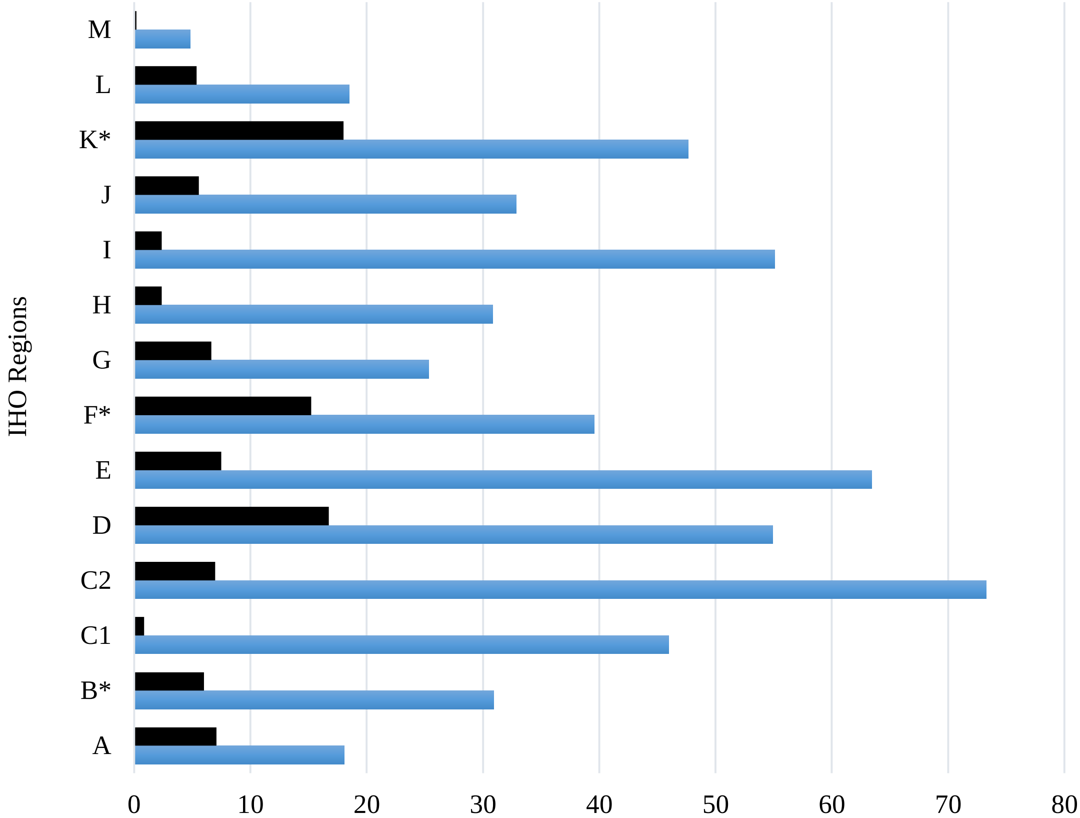


Figure 3.8 Chronicle comparison of stranded ships with serious and very serious consequences during ten - year period

From 2009 to 2019 year, of the total number of stranded ships, as many as 84.76 %, had serious or very serious consequences. Very serious stranding consequences are stranding, which includes complete loss of the ship, death, or serious pollution. In contrast, serious stranding consequences are the mechanical failure of the machinery, major damage to the superstructure, severe damage to the structure making the ship incapable of continuing navigation, pollution of the marine environment and/or failure, or damage that requires towing or shore assistance [45].

In accordance to Figure 3.8, the number of stranded ships has an oscillating trend. There was a significant increase in stranded ships with serious consequences during 2010 and 2017. In general, the number of stranded ships with large consequences is followed by strands with serious consequences. The most significant differences were observed during 2012 and 2013 when very serious consequences came to the fore. In the current period, the number of strands with very serious consequences is growing.

Considering the positive trend of stranding, with very serious consequences, comparison of the stranded ships and adequate surveyed area up to 200 m by IHO regions has been investigated from data available from [45]. The obtained results are shown in Figure 3.9.



	A	B*	C1	C2	D	E	F*	G	H	I	J	K*	L	M
Stranded ships	7,08	6	0,85	6,98	16,7	7,5	15,2	6,65	2,36	2,36	5,57	18	5,36	0,21
Surveyed<200m	18,1	30,9	46	73,3	54,9	63,5	39,6	25,3	30,9	55,1	32,9	47,7	18,5	4,83

Figure 3.9 Comparison of the stranded ships and adequate surveyed area up to 200 m by the IHO regions

Taking into consideration the observed ten-year stranding ship period, Figure 3.9, it can be determined which hydrographic regions are particularly risky. IHO regions D, F and K, have 50 % of all strands in the observed period. This fact suggests a high probability that maritime accidents and incidents will increase in the coming years, especially when it comes to cruise ships and merchant ships.

The choice of marginal routes is because of exotic areas, or because of decrease in the total cost of travel in the case of merchant ships [46]. Marginal pathways are either not adequately or not hydrographically measured at all [47].

The timely availability of maritime safety information is considered essential for the safety of navigation. It is, therefore, necessary to apply common standards in the collection, processing, and dissemination of information. Conducting a hydrographic survey is a time-consuming process and requires financial resources. It is reasonable to assume that the cost of conducting a hydrographic survey is one of the main reasons for the inadequate survey. Therefore, the next chapter analyses parameters as a function of a cost conducting the hydrographic survey.

4. ANALYSIS OF PARAMETERS AS A FUNCTION OF HYDROGRAPHIC SURVEY COST

Nautical charts and navigational publications must represent reality. Reality is partly dynamic and changeable in nature [48]. In order to monitor changes, the data obtained by the adequately conducted hydrographic survey are collected. It is assumed, that at this point, a high degree of development of technical and technological solutions in the implementation of a hydrographic survey. It can also be argued that maximally accurate methods are applied with the support of the technique [49], [50]. Despite this, according to data available to the IHO, more than 90 % of the world's oceans are represented by unreliable nautical charts and navigational publications [51]. It is reasonable to assume that one of the main factors of this problem is the cost of conducting a hydrographic survey. Therefore, it is necessary to classify and analyse the costs of the survey. Hence, this chapter analyses the cost ratio of hydrographic survey technologies and the parameters in the functions of the survey costs relating to platforms and survey area.

4.1. Cost ratio of hydrographic survey techniques

Depending on the hydrographic survey technology, the costs include costs of technical support and costs of equipment used. In order to obtain a detailed insight into the total costs of conducting a hydrographic survey, costs were analysed with regard to the selected measurement techniques. Hydrographic survey implementation techniques can generally be divided into traditional and modern, and they differ in terms of platforms and sensors, as shown in Figure 4.1.

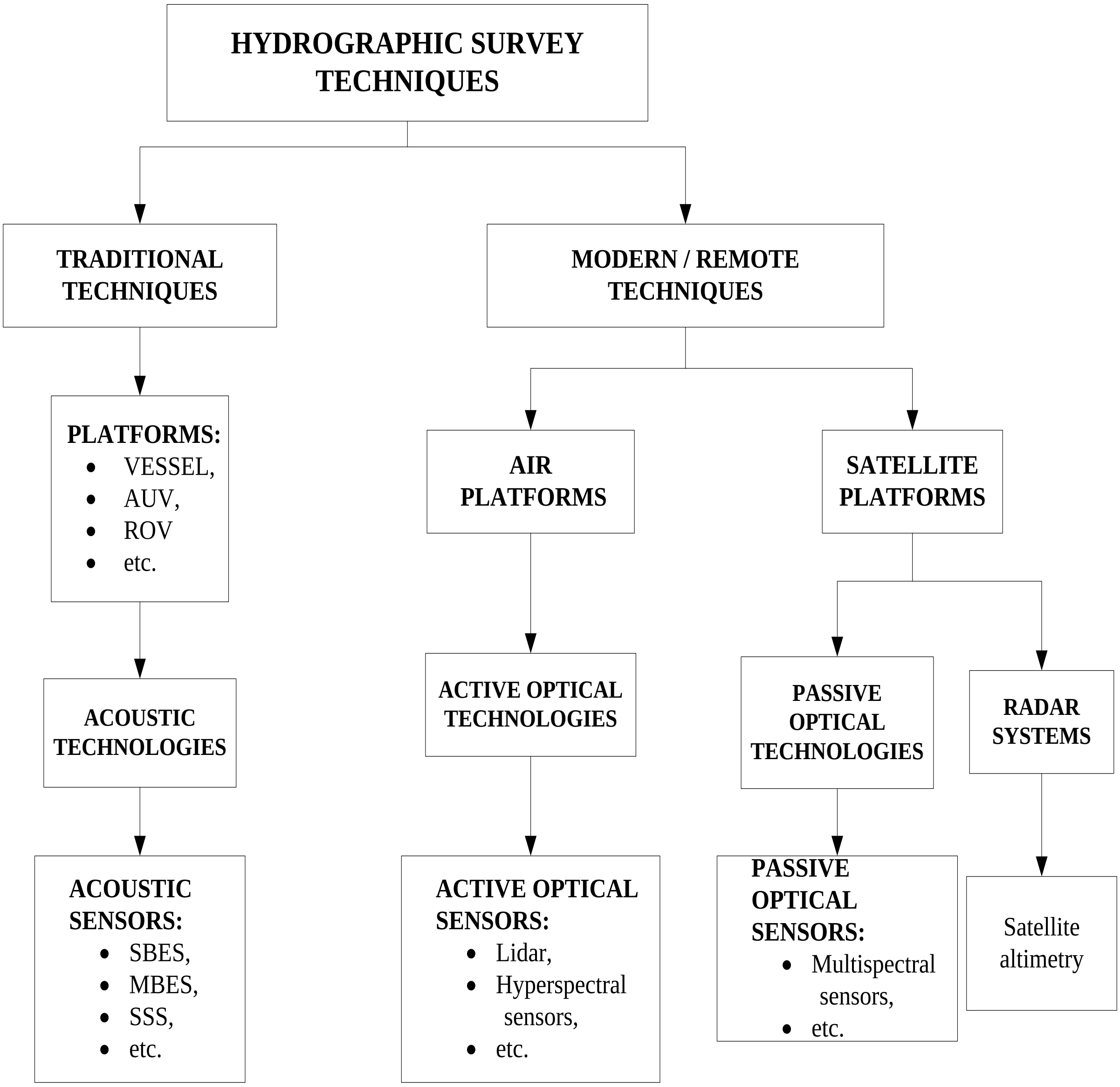


Figure 4.1 Distribution of hydrographic survey and bathymetry implementation technology

According to Figure 4.1, traditional technologies use marine technology support as a platform. Vessels, Remotely Operated vehicle – ROV, Autonomous Underwater vehicle – AUV, etc., are the most commonly used platforms. These platforms have an acoustic sensor that can be divided into Side Scan Sonar – SSS, Multibeam Echo Sounder – MBES, Single Beam Echo Sounder – SBES, etc.

On the other hand, modern technologies use air or satellite platforms and have optical sensors. Light Detection and Ranging – LIDAR, aerial multispectral and hyperspectral sensors, satellite, or aerial panchromatic imaging are often used optical sensors for modern hydrographic survey techniques. The equipment of both technologies represents a whole range of devices whose performance is constantly upgraded and improved.

Due to the technology of hydrographic survey implementation, there are oscillations in costs. This fact is confirmed, among other things, by data obtained in the framework of a scientific and research project of the British Department for the Environment, Food and Rural Affairs (DEFRA) [52]. The Project was related to the maritime framework strategy for the development of habitat indicators. The purpose was to identify the most cost-effective and high-quality survey method for habitat detection and analysis. Since the methods for bathymetry and hydrographic survey are also used, the data on the costs of individual survey methods per unit area[11] were taken from the mentioned Project. In order to clearly present the costs of a hydrographic survey depending on the technique, the collected data from the Project were analysed as the ratios of all investigated technologies related to the implementation of hydrographic measurement and bathymetry. The ratios are represented by a reciprocal matrix. The basic form of a reciprocal matrix is presented by expression (4.1):

$$A = \begin{bmatrix} 1 & a_{ij} & a_{ik} \\ 1/a_{ij} & 1 & a_{jk} \\ 1/a_{ik} & 1/a_{jk} & 1 \end{bmatrix} \tag{4.1}$$

The matrix is based on an expression (4.2):

$$a_{ij} = \frac{1}{a_{ji}}; for\ i, j \leq n \tag{4.2}$$

where is a_{ij} – the coefficient of the matrix in the i-th row and j-th column, n – is the number of alternatives being compared.

The analysed ratios between hydrographic survey technologies made according to [52] are presented by a matrix in Figure 4.2 and the list of the row and column marks from the matrix is shown in Table 4.1.

[11] The price is expressed in £ per km² and for all the above methods it is standardized according to the mean values of depths [52].

	A	B	C	D	E	F	G	H	I	J
A	1	0.58	0.5	0.2	0.2	0.2	0.1	0.1	0.1	0.1
B	1.7	1	0.9	0.4	0.3	0.3	0.3	0.2	0.1	0.1
C	1.9	1.1	1	0.4	0.3	0.3	0.3	0.3	0.2	0.1
D	4.6	2.7	2.5	1	0.8	0.8	0.7	0.6	0.4	0.3
E	5.5	3.2	3	1.2	1	1	0.8	0.7	4.8	0.4
F	5.5	3.2	3	1.2	1	1	0.8	0.7	0.5	0.4
G	6.8	3.9	3.6	1.5	1.2	1.2	1	0.9	0.6	0.5
H	7.5	4.3	4	1.6	1.4	1.4	1.1	1	0.7	0.5
I	11.5	6.7	6.2	2.5	2.1	2.1	1.7	1.5	1	0.8
J	14.4	8.3	7.7	3.1	2.6	2.6	2.1	1.9	1.2	1

Figure 4.2 Reciprocal cost ratio matrix of the mentioned hydrographic survey technologies

Table 4.1 A list of the row and column marks from the matrix and the corresponding characteristics

Marks	Platform	Type of sensor	Equipment
A	Unmanned Air Vehicle – UAV	Remote optical sensor	Satellite or aerial panchromatic imaging
B	Satellite	Remote optical sensor	Satellite imaging
C	Aircraft/helicopter	Remote optical sensor	Satellite or aerial panchromatic imaging
D	Vessel	Acoustic sensor	Single Beam Echo Sounder – SBES
E	Vessel	Acoustic sensor	Side Scan Sonar – SSS

F	Drones; Autonomous Underwater Vehicle – AUV and Remotely Operated Vehicle – ROV	Acoustic sensor	Side Scan Sonar – SSS
G	Aircraft/helicopter	Remote optical sensor	Light Detection and Ranging – LIDAR
H	AUV/ROV	Acoustic sensor	Multibeam Echo Sounder – MBES
I	Satellite/aircraft	Remote optical sensor	Aerial multispectral and hyperspectral imaging
J	Vessel	Acoustic sensor	MBES

The analysed technologies, in Figure 4.2, are shown in columns and rows depending on their cost. The cheapest equipment includes satellite or aerial panchromatic recording using a drone, while the most expensive refers to a multi-beam depth sounder using a vessel. Based on the analysis of the price ratios, it can be concluded that the price of individual equipment varies in relation to the hydrographic survey platform used. One example is the use of MBES and a ship, the price of which is almost twice as high as the use of MBES and drones. Therefore, it is necessary to analyse and compare the costs of the platform.

4.2. Parameters of platforms and survey area in the function of the hydrographic survey cost

Traditional hydrographic survey techniques are based on the usage of some offshore sensor platforms. Mentioned platforms are the vessel and underwater vehicles (drones). Drones can be divided into autonomous underwater vehicles and vehicle remotely operated [53], [54]. If modern techniques are chosen, air platforms such as airplanes, helicopters, or drones are used. Table 4.2 analyses and compares the costs of conducting a hydrographic survey depending on the selected platforms.

Table 4.2 Operational or running[12] costs of marine and air platforms

THE COSTS OF MARINE AND AIR PLATFORMS	**ASSOCIATED COST MARK [t]**				
	Vessel	**AUV**	**ROV[13]**	**Aircraft/ helicopter**	**UAV**
Technical costs (platform maintenance, repair of all components, etc.)	C_{v0}	C_{a0}	C_{r0}	C_{ah0}	C_{u0}
Supply costs (expenses for food, drinks, and other necessities of the crew)	C_{v1}				
Insurance costs (component insurance)	C_{v2}	C_{a1}	C_{r1}	C_{ah1}	C_{u1}
Fuel cost	C_{v3}			C_{ah2}	
Cost of renting flying equipment				C_{ah3}	
Battery charging cost		C_{a2}	C_{r2}		C_{u2}
Administrative costs (satellite phone, telefax, telex, e-mail, etc.)	C_{v4}				

From the Table 4.2 it is evident that the platforms of ships, planes, and helicopters have the highest number of parameters in the function of the costs. In addition to the air platform, modern remotely operated technology also includes satellite support. The cost of performing a hydrographic survey using these supports is as much as 90 % lower than traditional technology and aerial technology support [56]. The data obtained through satellite platforms does not meet the currently prescribed IHO requirements in the S-44 Hydrographic Survey Standards; therefore they are not analysed in Table 4.2. Nevertheless, these data can serve as a useful tool for planning and prioritization, especially with limited financial resources [57]. The parameters for reducing the cost of satellite platforms compared to other platforms are shown in Table 4.3.

[12] Running costs are the same as operational costs. Running costs is a term used in British and American literature in maritime transport.
[13] The ROV is connected by connecting cable to the mother ship [55]. Therefore, the costs of the ship must be included in the costs of the ROV.

Table 4.3 Parameters in the function of reducing the costs of a satellite platform [56]

Parameters	**Mark**
The mobilization of a vessel, aircraft or other platforms is unnecessary	p_{s0}
Drastically less staffing is required	p_{s1}
No risk to personnel associated with working in shallow water (as in the case of a vessel) or when plying in areas with variable topography (as in the case of air platforms)	p_{s2}
Permits to work in the research areas are not required	p_{s3}
There is no negative impact on the environment	p_{s4}
Short time required to achieve measurable results	p_{s5}
Others	p_{s6}

By analysing the data in Table 4.3, it can be concluded that using a satellite platform costs generally depends on the costs of satellite images. The costs depend on the image quality and can be free of charge [58]. The costs of individual satellite platforms are shown in Table 4.4.

Table 4.4 Cost of individual satellite scenes [59], [60]

Satellite	**Cost/km² (€)**
Ikonos	2.64
Quickbird	22
Pleiades	5
TerraSar – X	2.64
WorldView 2	14 - 60
WorldView 3 and 4	14 – 60
RapidEye	0.95
Sentinel 2	Free
Landsat 8	Free

Reducing the cost of conducting a hydrographic survey is not based solely on choosing a cheaper platform and equipment. The characteristics of the area where the survey is carried outplay an exceptional role in the implementation costs.

Not all areas require equal accuracy. Not all areas are available for all types of platforms and equipment; oceanographic and meteorological conditions are also not negligible parameters. The overall budget and urgency also play an important role. In order to obtain a complete analysis of all costs, it is proposed to consider the parameters that affect the trends in the costs of conducting hydrographic surveys, Table 4.5.

Table 4.5 Parameters as a function of costs of hydrographic survey implementation and associated marks

Parameters as a function of costs of hydrographic survey implementation	**Mark**
Required accuracy	p_{hi0}
Survey depths	p_{hi1}
The size of the area to be measured	p_{hi2}
The priority of the measurement area	p_{hi3}
The length of the sea route from the base station to the place of hydrographic survey	p_{hi4}
Platform velocity	p_{hi5}
Fuel costs	p_{hi6}
The time required for hydrographic survey	p_{hi7}
Staff costs	p_{hi8}
Bottom types (silt, sand, gravel, rocky, mixed bottom, etc.)	p_{hi9}
Coastal types (tectonic, erosive, biogenic, etc.)	p_{hi10}
Environmental conditions (rain, fog, cloud cover, wind, etc.)	p_{hi11}
Oceanographic conditions (water clarity, wave height, sea currents, etc.)	p_{hi12}
Others	p_{hi13}

The analysis of the costs of hydrographic organizations and the costs of hydrographic technologies led to several interdependent parameters. It is impossible to make a cost reduction model that would be used equally in all hydrographic survey situations and for all areas. It is also important to emphasize that it is impossible to determine the universal characteristics of any type of platforms or sensors. The characteristics are different depending on the manufacturer, model, components, etc. Accordingly, each hydrographic survey area has different characteristics. When choosing the most cost-effective technology, the criteria to be met must be satisfied. By setting the criteria, the required quality of the survey is maintained. The next chapter represents a methodology that can reduce the unit cost of hydrographic survey and meet the required quality.

5. METHODOLOGY OF MAKING THE OPTIMAL HYDROGRAPHIC SURVEY TECHNOLOGIES SOLUTION

Reducing the cost of implementing a hydrographic survey is an extremely difficult task. The simplest would be to choose the cheapest technology and equipment, but it is almost always necessary to meet other criteria in addition to the price. The criteria are not uniform and vary depending on the area of implementation of a hydrographic survey. Looking at the cost as the main criterion, there are situations when some areas require an urgent hydrographic survey, and accuracy is reduced in favour of speed of implementation. There is a wide range of scenarios that include different criteria and their relationships with each other, in order to achieve the most cost-optimal choice of technology for conducting a hydrographic survey in an area. This chapter explains a new method that includes a reduced binary elimination matrix as the first step in the optimal hydrographic technologies deciding process. The decision tree as one of the visualizations and classification methods is analysed. Finally, the Weighted Sum Model, as one of the multi-criteria optimization methods that combine computational and mathematical tools to assess the performance criteria by decision-makers subjectively, is explained. The method is represented and successfully published in [61].

5.1. Process of identifying the appropriate hydrographic survey technology

When choosing the optimal technology, it is necessary to identify as many parameters as possible. A detailed analysis of the survey implementation area is considered to be of extreme importance. After such an analysis, it is possible to approach the rational selection of the optimal platform and equipment while maintaining a certain level of quality of the survey itself. The process of identifying suitable and optimal technology for a hydrographic survey consists of two stages. The first stage represents the exclusive stage in which the formulation of the problem is performed. The second stage is the optimization stage, in which the model is built, and the final results of the model are obtained. The flowchart of the process is presented in Figure 5.1.

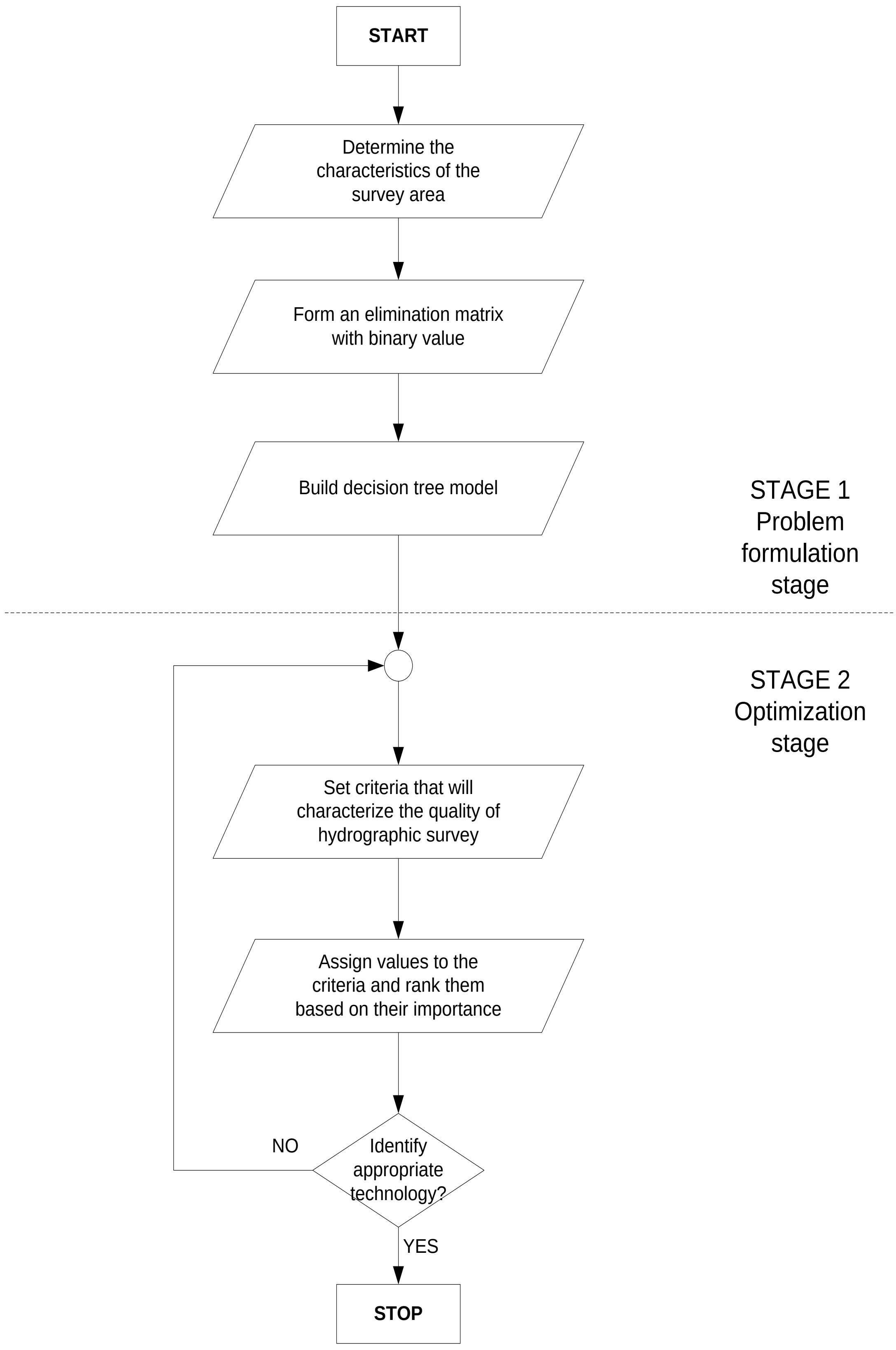


Figure 5.1 The process of identifying the appropriate technology

According to Figure 5.1, in the first stage, the decision tree model is built. This process begins with an examination of the characteristics of survey area. Then, the reduced binary elimination matrix is formed, which serves as an input variable for the decision tree model. Also, a decision tree is made based on the matrix. Furthermore, the advantage of the decision tree lies in the fact that it needs to be created only once, assuming that there are no changes in the elimination matrix, which implies that the performances of the technologies remain the same. Hence, these performances can change only if new technologies or upgrades of existing technologies become available.

The second stage starts with the evaluation of the built model by setting criteria for hydrographic survey quality. Then it follows quantifying and ranking criteria. Also, it has to be noted, that determining the criteria values ensure adequate quality in the optimization process. Finally, the last part of this stage is the result of optimization, i.e., ranking technologies from top to bottom. On the top is the optimal technology and on the bottom is the least optimal technology.

5.1.1. Problem formulation stage

5.1.1.1. Reduced binary elimination matrix

The problem formulation stage begins with the diversity of the areas in which the hydrographic survey is carried out. Therefore, it is of a paramount importance to identify the characteristics of an area. To facilitate this process, the proposed distribution of characteristics and sub-characteristics of an area is represented in Table 5.1.

Table 5.1 Proposed distribution of characteristics and sub characteristics of the survey area [62-84]

Characteristics of the survey area	Sub characteristics
A – survey area coverage per day	$\boldsymbol{a_1}$ ≤ 1 km²/day
	$\boldsymbol{a_2}$ 1.1 – 25 km²/day
	$\boldsymbol{a_3}$ 25.1 – 65 km²/day
	$\boldsymbol{a_4}$ > 65 km²/day
B – the minimum depth to be a survey	$\boldsymbol{b_1}$ ≤ 1 m
	$\boldsymbol{b_2}$ 1.1 – 5 m
	$\boldsymbol{b_3}$ 5.1 – 20 m

C – the maximum depth of survey area	c_1	≤ 25 m
	c_2	25.1 – 45 m
	c_3	> 45.1 m
D –a possibility of hazards to operation exists	d_1	a possibility of hazards to operation to aerial navigation exists
	d_2	a possibility of hazards to operation to surface navigation exists
	d_3	a possibility of hazards to underwater navigation exists
E – seabed type	e_1	rock/coral
	e_2	soft (mud/sand)
	e_3	heavy vegetation

Table 5.1 is made on the basis of reviewed literature [62-84]. It represents the framework that hydrographers or marine industry employees use. The literature references are used to obtain the minimum set of survey area data. The derived minimum set of survey area data together with survey technologies form the basis for elements of binary reduction matrix. Each identified characteristic has been divided by a single division into sub characteristics that are mutually exclusive.

From the Table 5.1, it can be seen that the five (5) distribution characteristics are proposed to create the basics framework of the survey area and as such form the basic elements for the binary reduction matrix. They are sorted into A, B, C, D, and E characteristics. Also, as it can be seen, each characteristic contains sub characteristics. Some characteristics have numerical values (A, B, and C), and some characteristics are descriptive (D and E).

The proposed distribution of characteristics and sub characteristics can be applied to any area and easily supplemented with new data as needed. It has to be pointed out that not all areas are available for all technologies.

Distribution A (survey area coverage per day) refers to the urgency of the hydrographic survey. For example, distribution A is divided into four (4) categories/variables: a_1, which covers a survey area of less than 1 km^2/day; variable a_2, the survey area coverage is between 2 and 25 km^2/day; variable $a_{3,}$ the survey area is between 26 and 65 km^2/day, and variable a_4 covers the survey area greater than 66 km^2/day.

The distribution B (the minimum depth to be surveyed), C (the maximum depth of a survey area), and E (seabed type) refer to the survey techniques with performance depending on the depth and seabed type. For example, the distribution B is divided into three (3) categories: variable b_1 includes those technologies which can give satisfactory results of work at depths less than or equal to 1 m, variable b_2 represents minimum survey depths between 2 and 5 m, and the last variable b_3 denotes the minimum depth to be surveyed between 6 and 20 m.

The distribution D (a possibility of hazards to operation exist) refers to the potential of some technologies to disable survey operation and should also be considered. It contains three (3) descriptive sub characteristics/variables. Variable d_1 describes the possibility of hazards to operation to surface navigation, variable d_2 describes the existence of a possibility of hazards to surface and underwater navigation, and variable d_3 describes the possibility of hazards to surface and underwater navigation.

Once survey area data are obtained, and the available technology is known, a reduced elimination binary matrix can be created. A hydrographer fills the elimination matrix based on survey area data and performances of available technologies. Regarding the knowledge of survey area data, these are the data that the hydrographer must be aware of for planning surveying. Also, as far as the knowledge of technologies performances is concerned, these data vary depending on the model, and they are available from the manufacturer. Therefore, filling the elimination matrix is a simple process, and it is performed by a hydrographer based on the available data. Since all available technologies are not suitable for all survey areas, the elimination matrix is used for rapid and transparent elimination of inappropriate technologies. Hence, the values from the elimination matrix represent the input in the decision tree model. The basic reduced binary elimination matrix is shown in Figure 5.2.

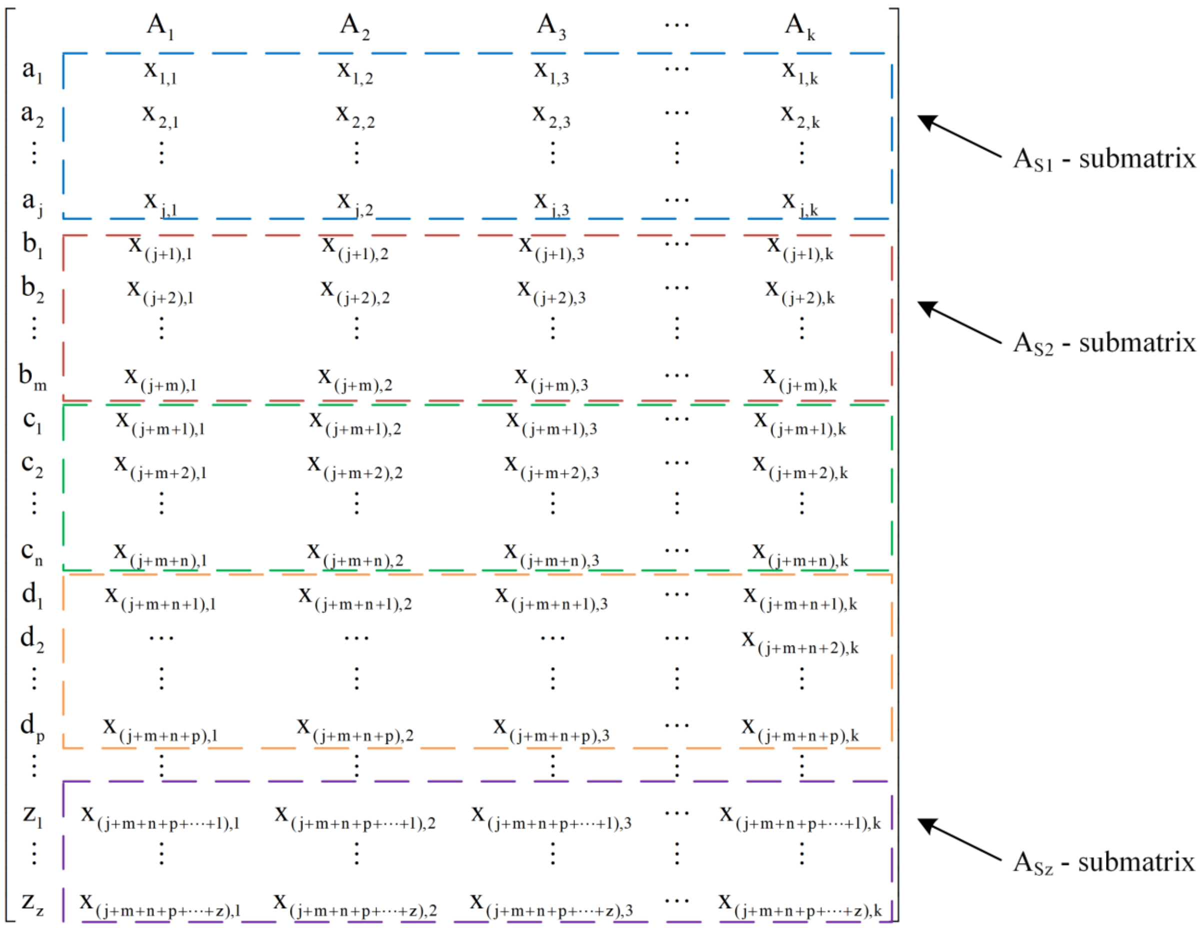


Figure 5.2 Reduced binary elimination matrix

The rows in Figure 5.2 represent characteristics and sub characteristics of the hydrographic survey area (such as survey area coverage per day, min/max depth, the possibility of hazard to operation, etc.), and the columns $A_1, A_2, A_3, \dots, A_k$ represent available technologies. The technologies are represented as alternatives that come into consideration. The reduced binary elimination matrix's element x_{kz} indicates the binary value (0 or 1) of k-th alternatives A_k with respect to the z-th characteristic survey area Ch_z, expressions (5.1) and (5.2):

$$A = \{A_1, A_2, A_3, \dots, A_k\} \tag{5.1}$$

$$Ch = \{A_1, B_2, C_{3,\dots,}Z_z\} \tag{5.2}$$

A binary filling is proposed to make the process simpler and faster. A value of 0 indicates that a particular alternative is not suitable for the specified area. Conversely, a value of 1 indicates that the observed alternative is suitable for the survey area characteristic. General characteristics of the survey area, to make the selection more precise, are divided into several sub characteristics, expression (5.3):

$$Ch = \{(a_1, a_2, \cdots, a_j), (b_1, b_2, \cdots, b_m), \ldots (z_1, z_2, \cdots z_z)\} \tag{5.3}$$

where $(a_1, a_{2,} \cdots, a_j)$ are sub-characteristics of A_1, $(b_1, b_2, \cdots, b_m)$ are sub-characteristics of B_2 and $(z_1, z_2, \cdots, z_z)$ are sub-characteristics of Z_z.

In practice, the number of characteristics in the matrix can be smaller than is suggested in Figure 5.2. If, for example, there is no possibility of hazard, then can be dropped from the matrix and not considered. Furthermore, each characteristic under consideration usually has only one sub characteristic. For example, the maximum depth is generally known, and it is represented by only one sub-characteristic. In contrast, the characteristic of the seabed type of the survey area does not have to be unambiguously defined. For example, the bottom part may be rocky, while the other part may be heavy vegetation. In such a case, two sub-characteristics of the seabed type are considered.

All available alternatives and sub-characteristics defined for a particular characteristic of the survey area define submatrices. The total number of submatrices depends on the total number of characteristics of the hydrographic survey area. Each submatrix must have a minimum of one non-zero column. Otherwise, the alternative to which the null column belongs will be excluded from further analysis. Such an outcome means that this alternative is not appropriate for the specified survey area. Also, it is important to note that if a technology is no longer available, the corresponding column from the matrix needs to be deleted. This procedure will not be reflected in other values in the elimination matrix.

The methodology for applying the suitable hydrographic survey technology based on a proposed binary matrix is represented by the flowchart in Figure 5.3.

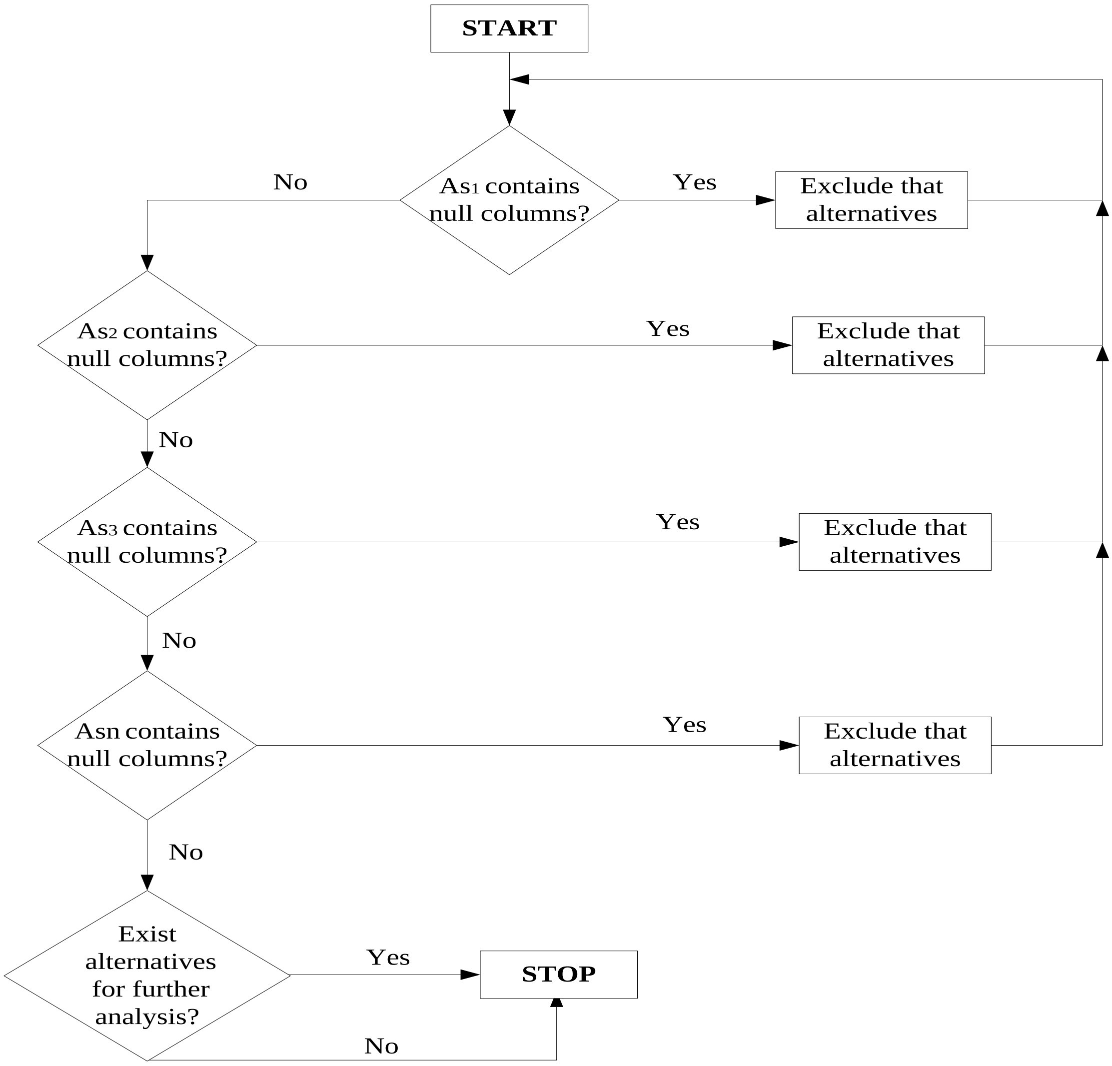


Figure 5.3 Flowchart of the proposed method with binary elimination matrix

Flowchart in Figure 5.3. is based on fuzzy rules. The process of identifying suitable technology with regard to the characteristics of the hydrographic survey area can be explained by the expression (5.4):

If submatrix A_{s1} contains null columns
then exclude that alternative and start again
else if submatrix A_{s2} contains null columns
then exclude that alternative and start again (5.4)
else if submatrix A_{sN} contains null columns
then exclude that alternative and start again
else indented alternatives for further analysis

The structural descriptions do not necessarily need to be represented as a set of rules. Hence, decision trees, which specify sequences of decisions that need to be made along with the resulting recommendation, are another popular means of expression [84].

5.1.1.2. A decision tree model

Decision tree learning is a supervised machine learning technique for inducing a decision from training data [85]. It represents probably one of the most intuitive and frequently used data science techniques [86]. The decision tree belongs to a class of supervised machine learning algorithms used to solve regression and classification problems [87]. In other words, it can be used to predict a discrete outcome and to predict a continuous numeric outcome. Classification trees are used to separate a dataset into classes belonging to the response variable. Usually, the response variable has two classes, 1 or 0 (yes or no). Regression trees are similar in function to classification trees and are used for numerical prediction problems when the response variable is numeric or continuous. It is a target variable that determines the type of decision tree needed [86].

The decision tree used aims to create a training model that can be used to predict the class or value of the target variable by learning decision rules used from the training data set. It is commonly used in operation research, specifically in decision analysis, to help identify a strategy most likely to reach a goal. Another use of it is as a descriptive means for calculating conditional probability. In general, a decision tree is used as a visual and analytical decision support tool, where the expected values or usefulness of competing alternatives are calculated [88]. The working process of a decision tree is shown in Figure 5.4.

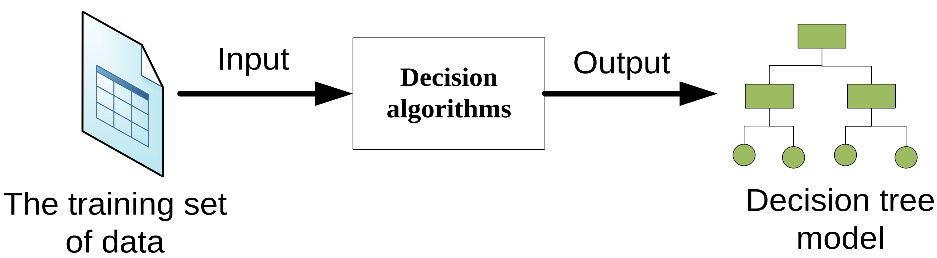


Figure 5.4 The working process of the decision tree

According to Figure 5.4, the working process of a decision tree starts with a training set of data. There are many different kinds of structure datasets. Both discrete and continuous variables can be used either as target or independent variables [9]. Dataset might have a simple logical structure involving just a few attributes, which can be captured by a decision tree [84]. Decision tree analysis can even deal with missing data. It can either classify missing values as a separate category that can be analysed with other categories or use a built decision tree model which can set the variable with lots of missing values as a target variable to make a prediction and replace these missing ones with the predicted value [89].

While some of the trees are more accurate than others, finding the optimal tree is computationally infeasible because of the exponential size of search space. Nevertheless, efficient algorithms have been developed to induce a reasonably accurate, albeit suboptimal, decision tree in a reasonable amount of time [90].

The algorithms for constructing decision trees usually build decision tree top-down by choosing a variable at each step that best splits the set of items [91]. Decision trees use multiple algorithms. The algorithm selection is also based on the type of target variables.

Notable decision tree algorithms include [89], [92-94]:

- CART - *Classification and Regression Trees*, this algorithm is applicable to a target variable representing continuous and categorical data. It generates a binary tree.
- QUEST - *Quick, Unbiased, Efficient, Statistical Tree*, and this algorithm is more suitable for multiple category variables but can only process binary data.
- CHAID - *Chi-Squared Automatic Interaction Detection* is based on adjusted significance testing. It can be used for prediction, as well as classification, and for detection of interaction between variables.
- ID3 - *Iterative Dichotomiser 3* algorithm builds decision trees using a top-down search approach. A greedy algorithm always makes the choice that seems to be the best at that moment.
- C4.5 – this is a successor of ID3, it builds decision trees from a set of training data in the same way as ID3.

The basic structure of the decision tree model is represented by Figure 5.5.

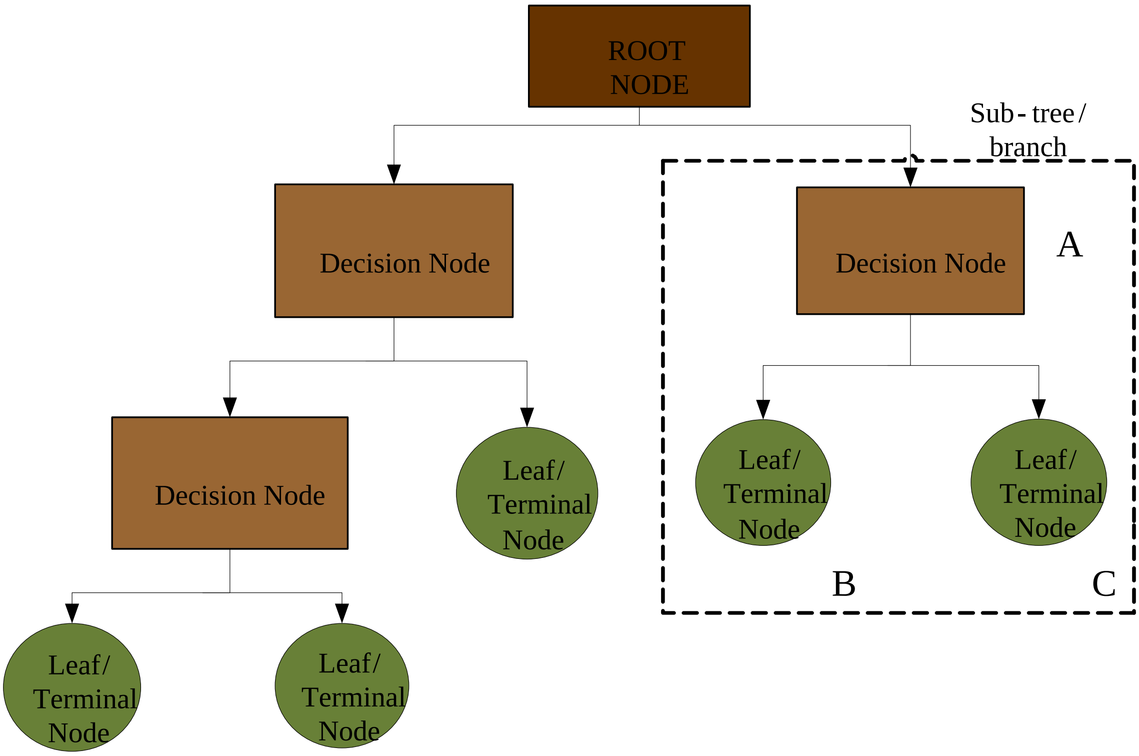


Figure 5.5 The general form of a decision tree model

A decision tree is a structure that includes a root node, decision node, and leaf node. The root node represents the whole sample that is further divided into sets of decision nodes. The process of dividing a single node into multiple nodes is called splitting. If a node does not split into further nodes, then it is called a leaf or terminal node. When a node gets divided further, the next node is termed a child node of the parent node.

Each decision node can be expressed as $s \epsilon \mathcal{N}^{Decision}$ and performs a split decision and routes a data sample x to the left leaf node $ll(s)$ or to the right leaf node $lr(s)$. When using axis-aligned chance decision, the split rule is based on a single chance feature $f(s)$ and threshold value $\theta(s)$, expressions (5.5) and (5.6), [95]:

$$x \in ll(s) \Leftrightarrow x_{f(s)} < \theta(s) \tag{5.5}$$

$$x \in lr(s) \Leftrightarrow x_{f(s)} \geq \theta(s) \tag{5.6}$$

All leaf nodes $l \in \mathcal{N}^{Leaf}$ store votes for the classes $y^l = (y_1^l, \ldots, y_C^l)$, where C is the number of classes [95].

The decision tree construction process continues iteratively until the required or set criteria are met as shown on Figure 5.6. If there were no stop criteria, the decision tree construction process would continue until leaf nodes are obtained for each individual sample. Suppose there is a set of stop criteria, such as a maximum depth that allows only a certain number of divisions from the root to the leaf node or a minimum number of samples in each node. In that case, the duration of the process is limited.

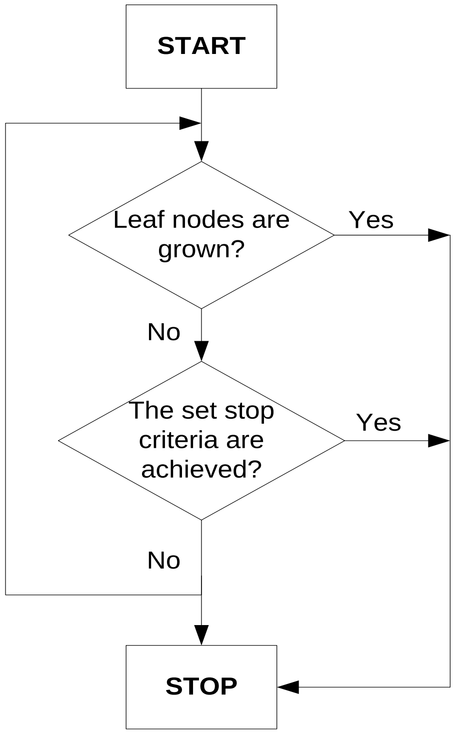


Figure 5.6 Iteratively decision tree construction process

In a decision tree, the idea is to split the dataset based on the homogeneity of data [96]. Many measures can be used to determine the best way to split the records. These measures are defined in terms of the class distribution of the attributes before and after splitting and are called *Attribute selection measures* or ASM [97]. The choice of the measure depends on classification or a regression problem. The two most popular attribute selection measures in the classification problem are the Gini index and Information gain [98].

Let L be a learning sample as in (5.7) [99]:

$$L = \{(x_1, c_1), (x_2, c_2) \dots (x_i, c_j)\} \tag{5.7}$$

where $x_1, x_2, \dots, x_i$ are a measurement vectors and $c_1, c_2, \dots., c_j$ are class labels.

The probability of an object being classified to a particular class can be expressed as in (5.8):

$$p_i = \frac{C}{L} \tag{5.8}$$

where p_i is the probability, and C is the class.

The Gini index determines the purity of a specific class after splitting along a particular attribute. The best split increases the purity of the sets resulting from the split. If L is a dataset with j different class labels, Gini is defined as in (5.9) [99], [100]:

$$ini(L) = 1 - \sum_{i=1}^{j} p_i^2\, g \tag{5.9}$$

If the dataset is split on an attribute A into two subsets L1 and L2, with sizes N1 and N2, respectively, Gini can be calculated as in (5.10) [99]:

$$gini_A(L) = \frac{N_1}{N} gini(L_1) + \frac{N_2}{N} gini(L_2) \tag{5.10}$$

Reduction in impurity is calculated as in expression (5.11) [99]:

$$\Delta gini(A) = gini(L) - gini_A(L) \tag{5.11}$$

Information gain is based on the Entropy. Entropy measures the extent of impurity or randomness in a dataset [101]. If all the subsets' observations belong to one class, the Entropy of that dataset would be 0. Otherwise, if the Entropy is higher, the uncertainty or impurity is higher. The Entropy is defined as the sum of the probability of each label times the log probability of that same label, expression (5.12) [99]:

$$entropy(L) = -\sum_{i=1}^{j} p_i log_2(p_i) \tag{5.12}$$

Information gain can be expressed as in (5.13):

$$IG(L, f) = entropy(L) - \sum_{v=1}^{V} \frac{|L^V|}{|L|} (entropy(L^V)) \tag{5.13}$$

where f is a feature, V are different values for a feature, $|L^V|$ is the subset of L with $f = v$.

In the regression problem, where the target variable is continuous, the attribute selection measure is variance reduction. Variance reduction indicates how homogenous nodes are. Expression (5.14) represent the standard formula of the variance:

$$Variance = \frac{\sum(X - \bar{X})^2}{n} \tag{5.14}$$

where X are actual values, $\bar{X}$ is the mean of the values, and n is the number of values.

Model evaluation is an important part of data science and decision tree. There are different evaluation metrics, some of them are for the regression model or classification model, and some are suitable for both, Figure 5.7.

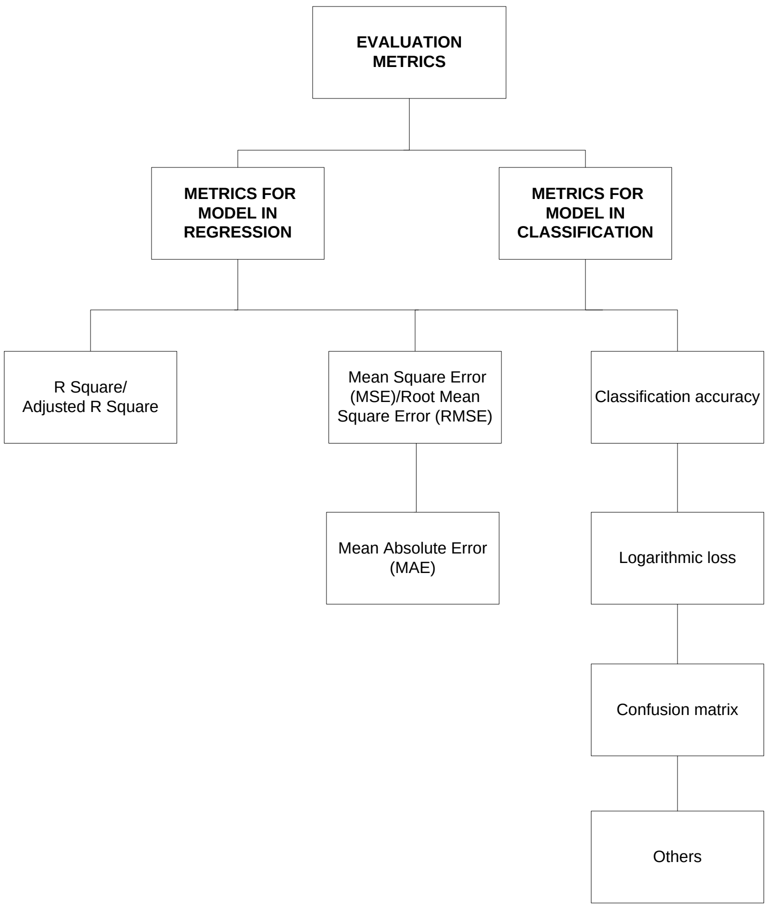


Figure 5.7 Evaluation metric for decision tree

The metrics used for both the regression and classification decision tree are Mean Square Error, Root Mean Square Error and Mean Absolute Error, presented by expressions (5.15), (5.16) and (5.17), [102]:

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2 \tag{5.15}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \tag{5.16}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - \hat{y}_i| \tag{5.17}$$

where N is the number of points in the dataset, i is the number of observations, y_i is the observed value and $\hat{y}_i$ is the predicted value.

MSE metric gives an absolute number on how much predicted results deviate from the actual number. RMSE is a quadratic scoring rule that measures the average magnitude of the error. It gives a relatively high weight to a large error; hence it is most useful when large errors are undesirable. MAE measures the average magnitude of an error in a set of predictions without considering their direction. It is a linear score, implying that all individual differences between predictions and corresponding observed values are weighted equally in the average [102].

In addition to the metrics shown so far, regression model metrics also includes R Square metric, expression (5.18) [102]:

$$R^2 = 1 - \sum \frac{(\hat{y}_i - y_i)^2}{(\hat{y}_i - \bar{y}_i)^2} \tag{5.18}$$

Classification accuracy or overall accuracy is a metrics that belongs exclusively to classification models and is represented by equations (5.19) [108]:

$$accuracy = \frac{number\ of\ correct\ predictions}{total\ number\ of\ predictions\ made} \tag{5.19}$$

Classification accuracy works well only if there is an equal number of samples belonging to each class. For multiclass classification Logarithmic Loss works by penalising the false classifications, expression (5.20):

$$logloss = \frac{-1}{N}\sum_{i=1}^{N}\sum_{j=1}^{M} y_{ij} * \log(p_{ij}) \tag{5.20}$$

where y_{ij} indicates whether or not sample i belongs to class j or not and p_{ij} indicates the probability of sample i belonging to class j.

A confusion matrix is an evaluation metric in the form of a matrix as an output and describes the complete performance of the model. The accuracy for the metric can be calculated by taking an average of the values lying across the main diagonal, expression (5.21) [108]:

$$accuracy = \frac{truepositive + truenegative}{totalsample} \tag{5.21}$$

where $truepositive$ is the case in which yes is predicted, and the actual output is also $yes,$ and the $truenegative$ is the cases in which no is predicted, and the actual output is no.

5.1.2. Optimization stage

After the technology suitable for the required hydrographic survey area is selected and visually substantiated by the decision tree, the process of identifying the optimal technology continues to the second stage. This stage represents the evaluation stage in which the model building is performed. When choosing the optimal technology for a hydrographic survey, it is crucial to include criteria. The criteria serve to ensure the required quality in the optimization process.

Multi-criteria decision making (MCDM) is a procedure that combines the performance of decision alternatives across several contradicting, qualitative, and/or quantitative criteria and results in a compromise solution [103], [104]. Relevant methods are frequently applicable, implacable or explicable, in numerous real-life problems.

They are widely used to evaluate sets of decision alternatives against conflicting criteria [104], [105]. The methods employed include Weighted Sum Methods (WSM), Analytical Hierarchy Process, Fuzzy Set Theory, Case-based Reasoning, Data Envelopment Analysis, ELECTRE, PROMETHEE, Simple Multi-Attribute Rating Technique, TOPSIS and among others [106].

The Weighted Sum Methods is also known as the weighted linear combination of scoring methods. It's probably the most commonly used MCDM approach [107-109]. It is a method often used in a single dimension issue [109]. The method is based on the weighted average. An evaluation score is calculated for each alternative by multiplying the scaled value given to the alternative of that attribute with the weights of relative importance directly assigned by the decision maker and followed by the summing of the products for all criteria. The advantage of this method is that it is a proportional linear transformation of the raw data, which means that the relative order of magnitude of the standardized scores remains equal [108].

The process of multi-decision and WSM consist of the following three steps, Figure 5.8.

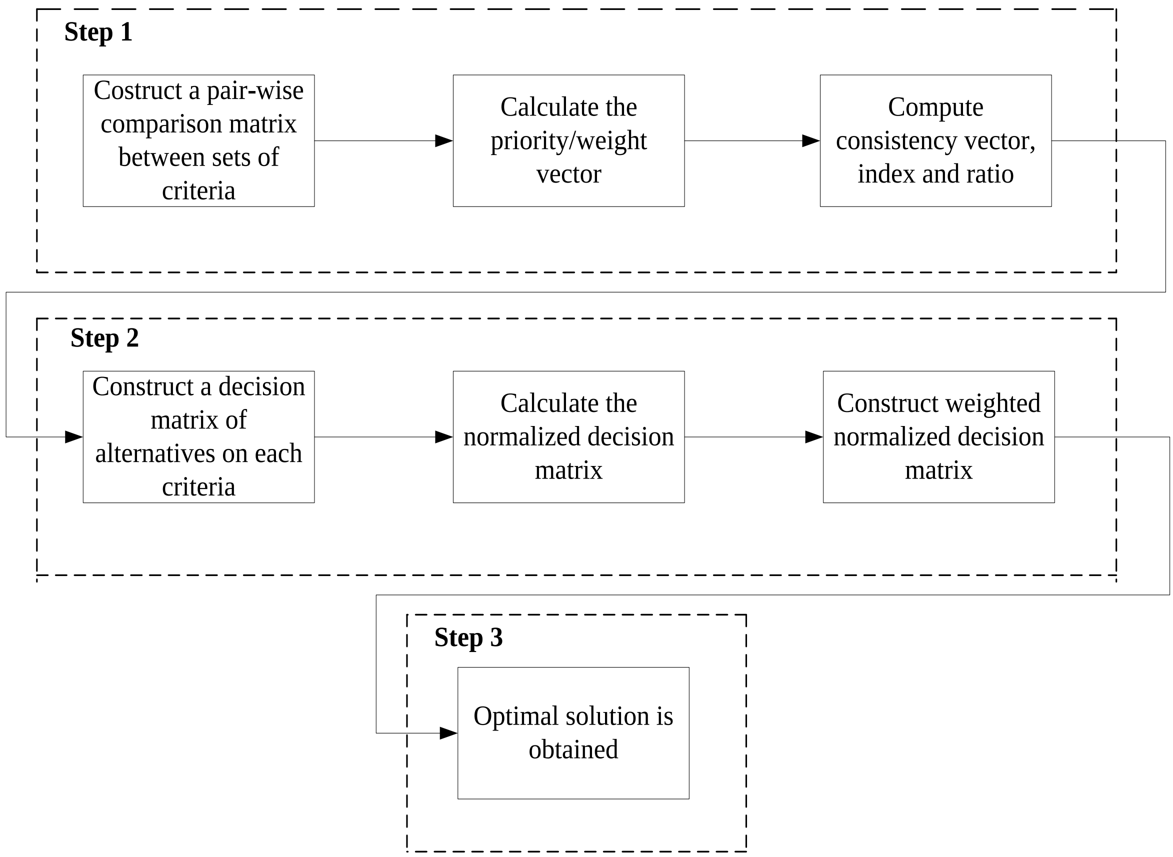


Figure 5.8 Working process of Weighted Sum Methods

In the first step in WSM, it is necessary to define the criteria. The criteria for selecting optimal survey technology is variable and depends on the required quality for specific hydrographic areas. Further, the hydrographer chooses the criteria's parameters based on the knowledge, experience, and area in question characteristics as a qualified person. It has to be pointed out, some areas require an urgent hydrographic survey, and then most often, the increase in implementation speed decreases the accuracy. But, there are areas where accuracy comes first and then costs and time come second. So, it is not wise to specify just one criterion because the hydrographic survey's quality would be impaired. Therefore, assuming that there are criteria, a pair-wise comparison matrix between sets of criteria with respect to the objective need to be constructed, expression (5.22):

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{bmatrix} \tag{5.22}$$

The pair-wise comparison is always assigned by Saaty's scale, as shown in Table 5.2.

Table 5.2 Saaty's comparison scale of pairwise comparisons [110-112]

Intensity of importance	**Definition**	**Explanation**
1	Same importance	Two elements are equally important
2	Intermediate values	When conciliation is required
3	Relatively more important	An element is slightly more important than the other
4	Intermediate values	When conciliation is required
5	Some more important	An element is more important than the other
6	Intermediate values	When conciliation is required
7	Very more important	All evidence shows a preference for one element over the other
8	Intermediate values	When conciliation is required
9	Enormously important	Maximum potential validity

Table 5.2 exhibits the scale of number that indicates how many times more important or dominant one element is over another element. Such a uniform scale facilitates the comparison process.

Once a comparison matrix has been made, it is necessary to sum the values in each column of the pair-wise matrix, compute each element of the matrix by its column total and calculate the priority or weight vector by finding the row averages, expression (5.23) [110], [113], [114]:

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} \frac{\sum_{j=1}^{n} \frac{c_{1j}}{\sum_{j=1}^{n} c_{1j}}}{n} \\ \frac{\sum_{j=1}^{n} \frac{c_{2j}}{\sum_{j=1}^{n} c_{2j}}}{n} \\ \vdots \\ \frac{\sum_{j=1}^{n} \frac{c_{nj}}{\sum_{j=1}^{n} c_{nj}}}{n} \end{bmatrix} \tag{5.23}$$

The weighted sum matrix is found by multiplying the pair-wise comparison matrix and the weight vector. Dividing all the elements of the weighted sum matrix by their respective priority vector element, a consistency vector CV is obtained, expression (5.24) [110], [114]:

$$CV = \begin{bmatrix} \frac{\sum_{j=1}^{n} c_{1j} \cdot w_j}{w_1} \\ \frac{\sum_{j=1}^{n} c_{2j} \cdot w_j}{w_2} \\ \vdots \\ \frac{\sum_{j=1}^{n} c_{nj} \cdot w_j}{w_j} \end{bmatrix} \tag{5.24}$$

The final stage of step 1 is to calculate the Consistency Index CI and Consistency Ration CR. The consistency Index measures the degree of inconsistency, as follows in equation (5.25):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5.25}$$

where n is matrix size and λ_{max} is the largest principal eigenvalue of the positive reciprocal pair-wise comparison matrix.

If the paired comparisons are perfectly consistent, then λ_{max} is equal to the size of the matrix and the $CI = 0$. The larger the inconsistency between comparisons is a consequence of the larger λ_{max} and the larger CI [115].

The consistency ration CR is calculated as follows in equation (5.26):

$$CR = \frac{CI}{RI} \tag{5.26}$$

where RI is the Random Consistency Index obtained from a randomly generated pair-wise comparison matrix.

If CR ≤ 0.1, then the comparisons are acceptable. However, if CR > 0.1, then the values of the ratio are indicative of inconsistent judgments. In such a case, the judgments should be reconsidered and revised [108], [110], [114], [116]. Table 5.3 shows the value of the RI from matrices of order 1 to 10, as suggested by Saaty.

Table 5.3 Random Consistency Index

Size of matrix	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

In the second step of the working process of WSM it is necessary to construct a decision matrix ($m\ x\ n$) of alternatives on each criterion, expression (5.27):

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mm} \end{bmatrix} \tag{5.27}$$

The next part of the second step includes calculating the normalized decision matrix for positive attributes, equation (5.28) and construct weighted normalized decision matrix R', expression (5.29):

$$r_{ij} = \frac{x_{ij}}{x_{ij}^{max}} \tag{5.28}$$

where x_{ij}^{max} – is a maximum number of r in the column of j.

$$R' = \begin{bmatrix} w_1 \cdot r_{11} & w_2 \cdot r_{12} & \cdots & w_n \cdot r_{1n} \\ w_1 \cdot r_{21} & w_2 \cdot r_{22} & \cdots & w_n \cdot r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_1 \cdot r_{m1} & w_2 \cdot r_{m2} & \cdots & w_n \cdot r_{mn} \end{bmatrix}; \sum_{j=1}^{n} w_j = 1 \qquad (5.29)$$

The final step in WSM includes the optimum solution of each alternative and is obtained by the following equation (5.30) [112], [114]:

$$S_i^{WSM} = \sum_{j=1}^{n} r_{ij} w_j \, ; i = 1,2,3, \dots, m \qquad (5.30)$$

where S_i^{WSM}represents the weighted sum score, r_{ij} is the score of the i-th alternative with respect to the j-th criterion and w_j is the weight of the j-th criterion.

It has to be highlighted that the methodology can be applied to all survey areas and all available technologies. The first step involves the obtained hydrographic survey area data. A reduced elimination binary matrix contains the distribution of characteristics and sub-characteristics of a hydrographic survey area and available technologies, which is the main scientific contribution of the dissertation. Further, it has to be pointed out that the technologies' performances are available from the manufacturer. Hence, the reduced binary matrix presents an input to make a decision tree. Next, optimization criteria are determined based on the required quality for a specific survey area based on a financial budget, the time available, the desired level of accuracy, and other criteria chosen by the hydrographer. Finally, with the implementation of the suggested methodology, the working hypothesis, purpose, and general objectives of this research have been achieved.

6. CASE STUDY

This chapter focuses on implementing a novel method to evaluate suitable alternatives for hydrographic surveys considering the specific survey area. In the proposed case study, Kaštela Bay represented the hydrographic area of interest. Kaštela Bay represents a geographically defined whole that encompasses the area between Trogir to the west and Split on the east. The favourable nature features have influenced the intensive population throughout the history. Therefore, the numerous underwater finds are not surprising. The last underwater find was found in 2020. It was a wreck of a Roman imperial ship dating from the 1st century BC [117]. Such data can be directly related to poor knowledge of the seabed in the area. Therefore, this area was chosen for the case study. This chapter is structured in such a way as to show the workability of the methodology proposed in the previous chapter. The binary elimination matrix, the decision tree model, based on the data from the matrix, and finally, the weighted sum method for choosing optimal technology following the given criteria for Kaštela Bay is represented.

6.1. Case study and dataset

The study site is Kaštela Bay. It is a semi-enclosed coastal and the largest bay situated in the Middle Adriatic. The Bay is located at 43°32'00" N and 16°21'00" E [118]. It is 14.8 km long, approximately 6 km wide, and the total area is 61 km² [118], [120]. The Bay is relatively shallow with an average depth of 23 m. The maximum depth is 45 m at the bay's inlet. Heavy traffic across this area is under the jurisdiction of the Harbour Master's Office and the Port Authority Split which consists of passenger ports, trade ports, industrial ports, navy port and a large number of ports and moorings for small boats [118]. Nautical tourism port “Marina Kaštela” in Kaštel Gomilica with 420 moorings, is the largest port of nautical tourism in area. It significantly contributes to the development of nautical tourism and density of maritime transport [121]. The seabed consists of many different substrate types, including sand, rock, mud, and gravel [122]. The detailed bathymetry of Kaštela Bay with indicated navigation marks is shown Figure 6.1.

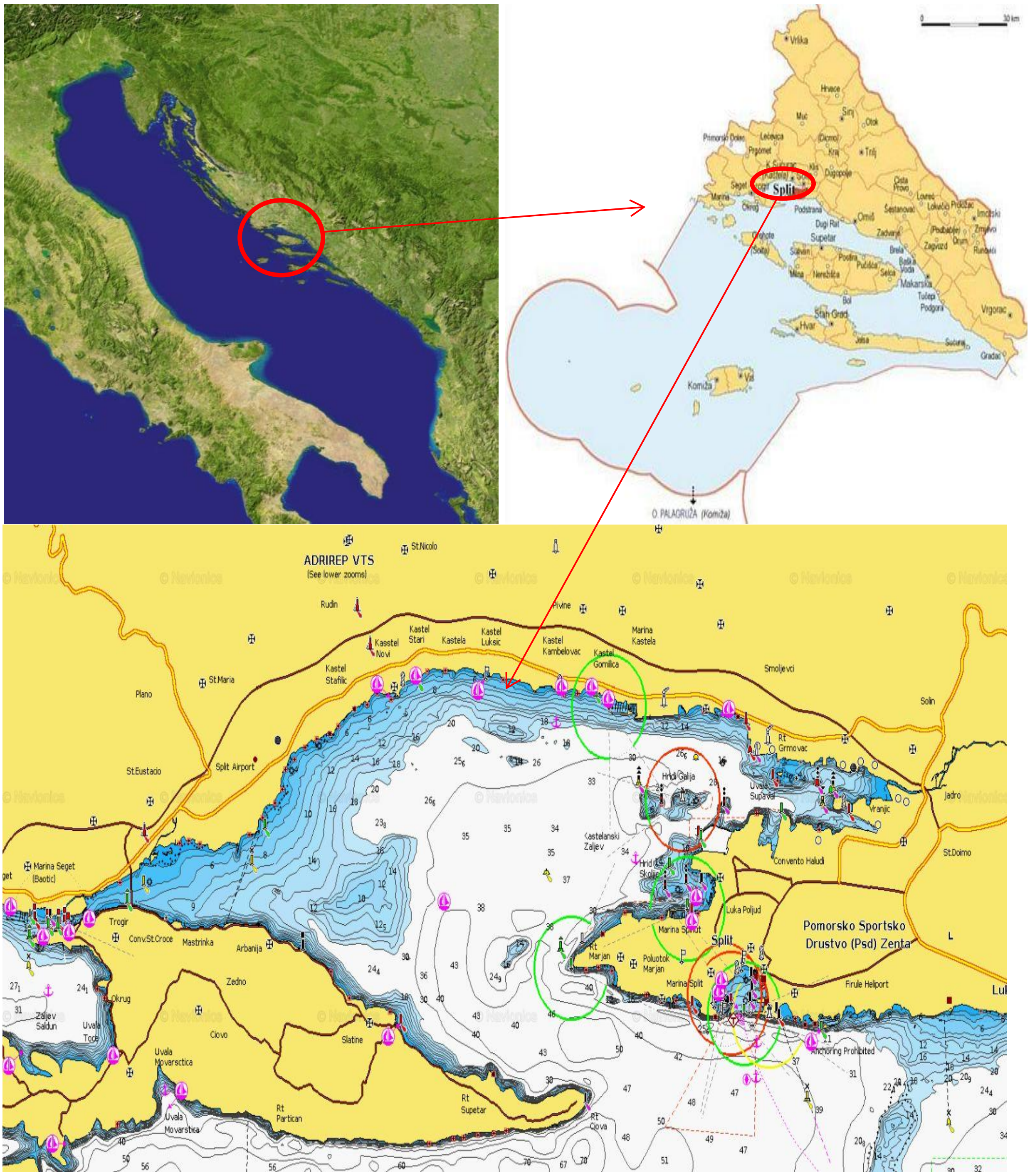


Figure 6.1 Adriatic Sea and Kaštela Bay [123], [124]

The hydrographic survey in Kaštela Bay by single beam echo sounder (SBES) and side scan sonar (SSS) was performed [125]. It is reasonable to assume that the hydrographic survey has not been repeated with more reliable technologies due to its cost and time. This model selects the optimal hydrographic survey technology according to the given criteria.

In the study case, the choice of alternatives is based on the technologies available to HHI and those technologies that would possibly be implemented in the future if their purchase or lease proves profitability, Table 6.1.

Table 6.1 Hydrographic survey technologies (sensors and survey platforms)

Alternatives	**Descriptions**
A_1	SBES (research vessel)
A_2	SBES + SSS (research vessel)
A_3	MBES (research vessel)
A_4	MBES (research vessel) + SBES (small boat)
A_5	LIDAR (UAV)
A_6	SDB (satellite sensors)

According to the novel method explained in the previous chapter, the first step involves examining the characteristics of the survey area. Given the diversity of the areas in which the hydrographic survey is carried out, identifying the characteristics of the area is of crucial importance in the formulation of the problem. To facilitate this process, the proposed distribution of characteristics and sub-characteristics of an area is represented in the previous chapter, Table 5.1.

Once survey area data are obtained (Table 5.1) and the available technology is known (Table 6.1), a reduced elimination binary matrix can be created, as shown in Table 6.2.

Table 6.2 Reduced binary elimination matrix with corresponding submatrices [62-84]

	SBES (RV)	SBES+SSS (RV)	MBES (RV)	MBES (RV)+SBES (boat)	LIDAR (UAV)	SDB
a_1	1	1	1	1	1	1
a_2	0	1	1	1	1	1
a_3	0	0	0	1	1	1
a_4	0	0	0	0	0	1
b_1	0	0	0	0	1	1
b_2	1	1	0	1	1	1
b_3	1	1	1	1	1	1
c_1	1	1	1	1	1	1
c_2	1	1	1	1	1	1
c_3	1	1	1	1	0	0
d_1	1	1	1	1	0	1
d_2	0	0	0	0	1	1
d_3	1	0	1	1	1	1
e_1	1	1	1	1	1	1
e_2	1	1	1	1	1	1
e_3	1	1	1	1	0	1

Table 6.2 is filled with elements based on the reviewed literature [62-84] because the performance of the alternatives is not uniform. Therefore, in practice, this should be completed by the hydrographer. From Table 6.2, for example, in the case of MBES (RV) technology, it is evident that survey coverage per day (characteristic A) is a maximum of 25 m (sub-characteristics a_1 and a_2). In terms of characteristic B, it can also be used in relatively shallow water (sub-characteristics b_3). The maximum depths (characteristic C) at which the MBES shows good performance are up to 45 m. Since its functionality does not include air or underwater navigation, it can also be used when there is a possibility of hazards to air and/or underwater navigation. Hence, a value of 1 belongs to d_1, and d_3 of characteristic D. Analogously, MBES can work even when the seabed is rocky or coral, soft or covered with vegetation (sub-characteristic e_1, e_2 and e_3).

In line with the above mentioned, for example, in the case of SDB technology, it has the highest coverage per day (sub-characteristics a_1, a_2, a_3, a_4) compared to all available technologies. It is not in danger of working in shallow waters (characteristic B), but its disadvantage is the inability to function adequately in deeper water (characteristic C). Furthermore, it has no direct contact with the air, water surface and/or underwater, so possible hazard does not pose a danger.

The data from Table 6.2 represent a set of training data in the decision tree working process. Based on these data, a general decision tree model was created with the software package *RapidMiner version 9.8*. It is one of the most used open-source predictive analytics platforms utilized for data analysis. It is accessible as a stand-alone application for information investigation and a data mining engine to be integrated into products. *RapidMiner* provides an integrated environment for data mining and machine learning procedures [126], [127].

Rapid miner provides a graphical user interface (GUI) used to design and execute analytical workflows. Those workflows form a process, which consists of multiple Operators. GUI allows connecting the operators in the process view. Each independent operator carries out one task within the process and forms the input to another operator's workflow. The primary function of a process is to analyse the data retrieved at the beginning of the process [126], [127]. Figure 6.2 shows a decision tree model based on data from the reduced binary elimination matrix made using *RapidMiner*.

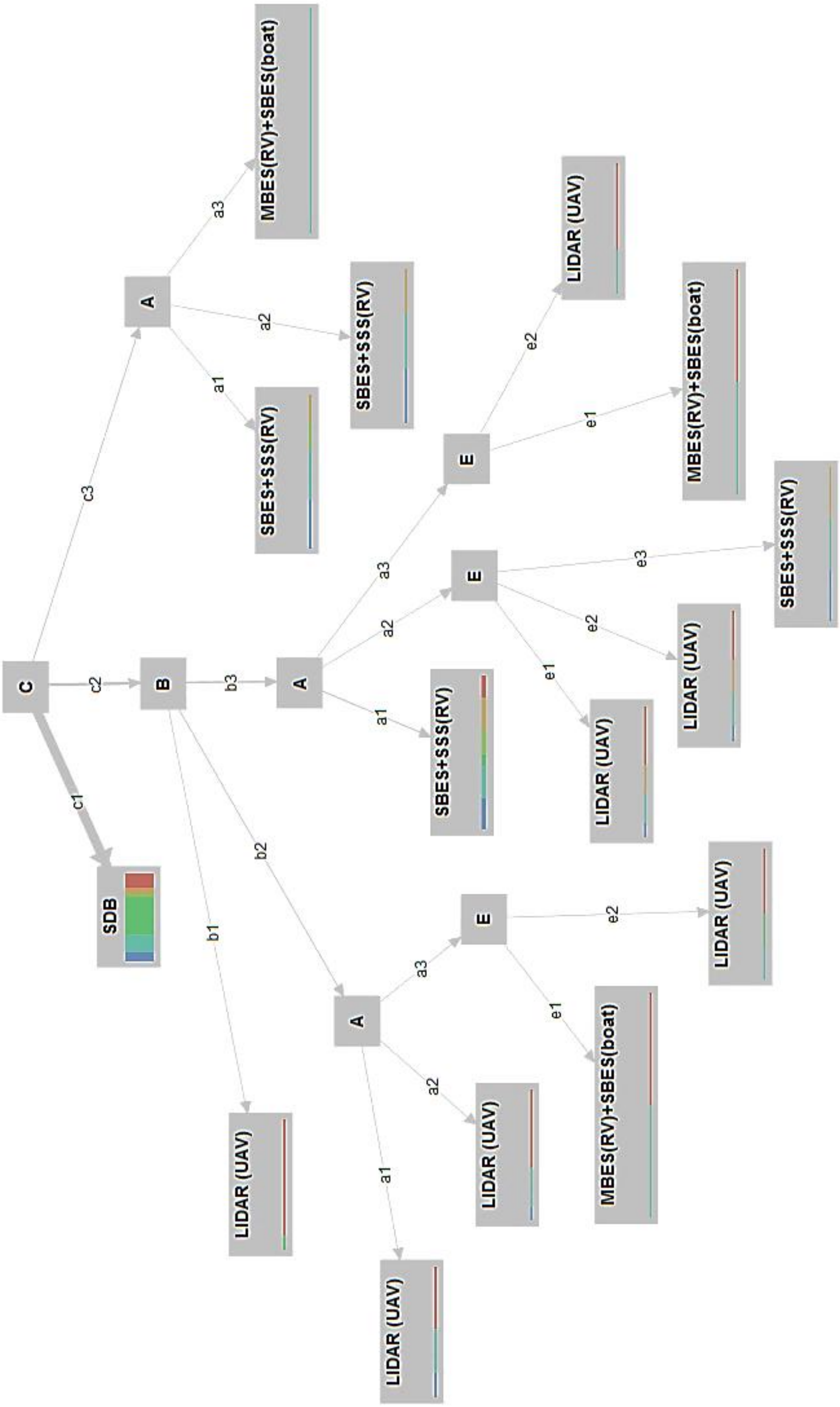


Figure 6.2 A decision tree model

The decision tree, from Figure 6.2, provides insight into all possible outcomes with respect to the selection of characteristics and sub-characteristics of an area. The root node is characteristic **C** which, according to Table 6.2, shows the survey area maximum depth. The root node was selected using the gain ratio algorithm when training the tree. This algorithm is a variant of information gain that adjusts each attribute information gain to allow the breadth and infirmity of the attribute values. Knowing the sub-characteristics of the root node, the branches of the tree lead to decision nodes **A**, **B** and/or **E**. Following their sub-characteristics, the next decision node or terminal node is reached. The terminal nodes represent the final decision and refer to the optimal technology.

Sometimes individual characteristics and sub-characteristics denote only one technology, and sometimes they refer to several of them. This is exactly what explains multicolours. The name of the technology of a terminal node depends on the data used for tree training and depending on the percentage of probability of that technology as an output value. Multicolours of nodes explain the possibility of choosing several technologies.

Once a general overview of the reduction binary elimination matrix concerning the general characteristics is made and once a decision tree model is made, it is easy to approach a more precise one. The characteristics and sub-characteristics of hydrographic survey area Kaštela Bay, as a case study, are shown in Table 6.3.

Table 6.3 Characteristic and sub-characteristics of the hydrographic survey area

A – survey area coverage per day	**B** – the minimum depth to be surveyed	**C** – the maximum depth of survey area	**E** – seabed type of area
$\boldsymbol{a_1}$ - ≤ 1km²/day	$\boldsymbol{b_3}$ – 6 - 20 m	$\boldsymbol{c_2}$ – 45 m	$\boldsymbol{e_1 + e_2}$ – mixed type

Given the specific area data from Table 6.3, a reduced binary elimination matrix was created in Table 6.4.

Table 6.4 Reduced binary elimination matrix for case study

	A_1	A_2	A_3	A_4	A_5	A_6
a_1	1	1	1	1	1	1
b_3	1	1	1	1	1	1
c_3	1	1	1	1	1	1
e_1	1	1	1	1	1	1
e_2	1	1	1	1	1	1

Values of 1 in the elimination matrix indicate the suitability of using all observed technologies concerning hydrographic survey characteristics of Kaštela Bay. To get a clearer picture, to shorten the budget time, to avoid the possibility of errors, and to gain the necessary knowledge, it is proposed use a decision tree model. This study's exclusive area of interest was obtained using the general tree in Figure 6.2 and shown in Figure 6.3.

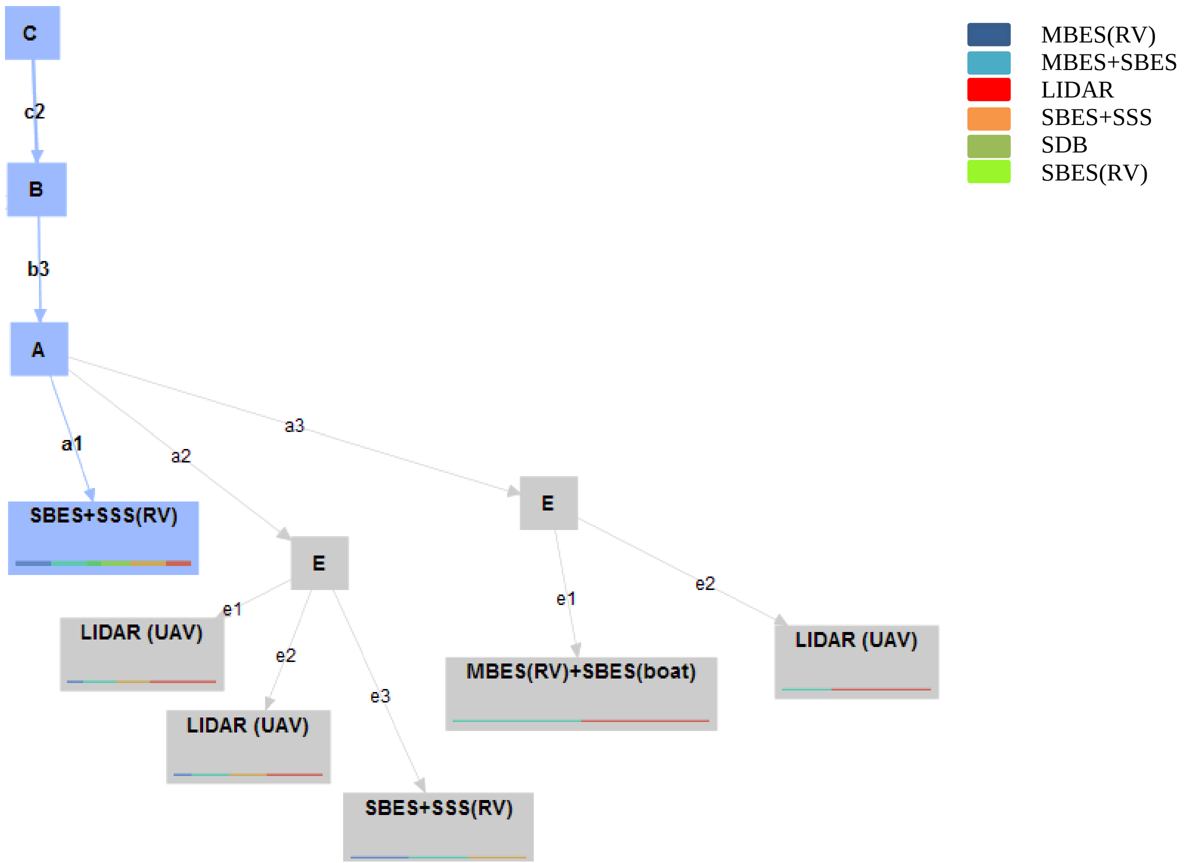


Figure 6.3 The decision tree model for Kaštela Bay study case

According to Figure 6.3 is evident that equal results were obtained. Figure 6.3 confirms the state from the reduced binary elimination matrix that all observed technologies are suitable for hydrographic surveys in Kaštela Bay. Therefore, they are taken as available alternatives for choosing the optimal solution. Three criteria perform multi-criteria decision-making: cost, accuracy, and urgency. Hence, the WSM method procedure was continued. Table 6.5 discusses the criteria used for the MCDM problem.

Table 6.5 List of criteria

Marks	Description
C_1	Cost
C_2	Accuracy
C_3	Urgency

The schematic representation of the MCDM process for the case study with respect to selected criteria is illustrated in Figure 6.5.

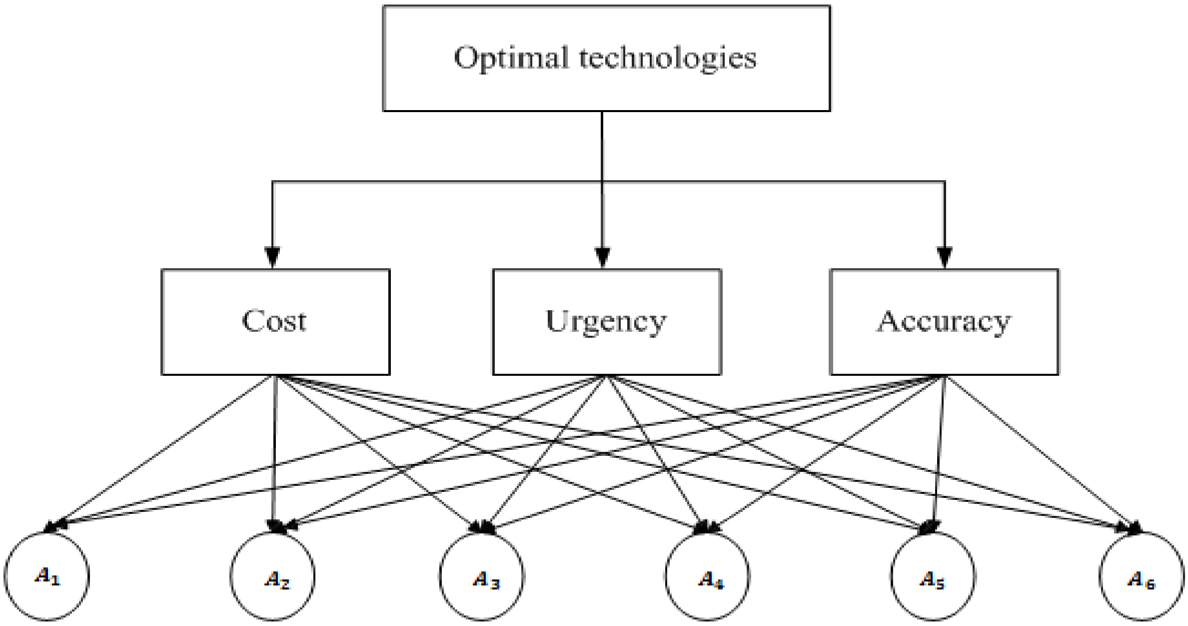


Figure 6.4 Structure of the multi decision problem

In Figure 6.5, a complex decision problem of choosing optimal hydrographic survey technologies in Kaštela Bay is represented as three level structures. The problem is at the top, the second level is criteria that affect the decision, and the last levels are decision options or alternatives. The development of a pairwise comparison matrix is presented in Table 6.6.

Table 6.6 Pairwise comparison matrix

Criteria	C_1	C_2	C_3
C_1	1	3	9
C_2	0.33	1	3
C_3	0.11	0.33	1
Σ	1.44	4.33	13

According to Figure 6.8, it is possible to conclude that criterion cost C_1 is chosen as preferred, it is followed by the criterion accuracy C_2 follows and the least important criterion is urgency C_3. The normalized pairwise comparison matrix and calculations of sum, weights vector, and consistency vector are shown in Table 6.7.

Table 6.7 Normalized pairwise comparison matrix, weights, and consistency vector

Criteria	C_1	C_2	C_3	**Σ**	**weights vector**	**CV**
C_1	1	3	9	2.0795	0.6932	2.9998
C_2	0.33	1	3	0.6907	0.2302	3.0004
C_3	0.11	0.33	1	0.2294	0.0764	3.0026

Consistency index and consistency ratio are obtained in expressions (6.1) and (6.2):

$$CI = \frac{\lambda_{max} - n}{n - 1} = 0.00045 \tag{6.1}$$

$$CR = \frac{CI}{RI} = 0 \tag{6.2}$$

The consistency rate is < 0.1 and it indicates sufficient consistency; therefore, the SAW method's procedure is continued. Table 6.8 shows the relationship between the practical alternatives and given criteria.

Table 6.8 Collected data based on scale values (1-5)

	C_1	C_2	C_3
A_1	3	3	3
A_2	3	4	3
A_3	4	5	4
A_4	4	5	4
A_5	3	2	5
A_6	5	1	5

In Table 6.8 the ratio is shown by grades 1 – 5 as in the school approach. The grades explain the suitability of alternatives with respect to observed criterion, completely suitable – 5, suitable - 4, partially suitable – 3, low suitability – 2, unsuitable – 1. Based on table 6.9, the normalized decision matrix is made and expressed in Table 6.9.

Table 6.9 The normalized decision matrix

	C_1	C_2	C_3
A_1	0.6	0.6	0.6
A_2	0.6	0.8	0.6
A_3	0.8	1	0.8
A_4	0.8	1	0.8
A_5	0.6	0.4	1
A_6	1	0.2	1

The values of the normalized decision matrix, from Table 6.10, are multiplied by the weights vector from Table 6.7 and finally, the ranked technologies for the hydrographic survey are obtained and shown in Table 6.10.

Table 6.10 Ranked technologies for the survey area

Alternatives	Score
SBES (research vessel)	0.60
SBES + SSS (research vessel)	0.65
MBES (research vessel)	0.97
MBES (research vessel) + SBES (small boat)	0.97
LIDAR (UAV)	0.58
SDB (satellite sensors)	0.82

From Table 6.10, the optimal technologies following the given criteria for Kaštela Bay are alternative $\boldsymbol{A_3}$ - MBES (research vessel) and $\boldsymbol{A_4}$ - MBES (research vessel) + SBES (small boat). Other available alternatives have significantly lower score. There is a small evident difference between the alternatives $\boldsymbol{A_1}$, $\boldsymbol{A_2}, \boldsymbol{A_3}$ and $\boldsymbol{A_5}$, which have a WSM score in the range from 0.58 – 0.65. These numerical results suggest that mentioned alternatives will not be taken for the observed hydrographic survey area. With this approach, it is possible to look at all available alternatives and all criteria concerning some areas and realistically decide on the optimal technology.

7. CONCLUDING REMARKS

Hydrographic surveys are carried out according to the standards prescribed by the International Hydrographic Organization (IHO). Hydrographic technologies and requirements are continuously evolving. Hence, IHO has adopted standards and recommendations for conducting hydrographic surveys to achieve maximum standardization of nautical charts, navigation publications, services, and hydrographic surveying practices.

Despite many efforts, the state of the hydrographic survey remains unsatisfactory. This fact has been confirmed and represented in this thesis. Using the data acquired from the IHO publication C-55 and standard statistical metrics such as the average value, an analysis of the hydrographic survey status at the world seas was conducted. The research concluded that at depths up to 200 m, approximately 10 % of the total number of seas listed in the C-55 performed an adequate hydrographic survey in the range of 90 – 10 %. However, at depths over 200 m, almost 60 % of the listed seas have more than 90 % of their territory unsurvey.

The increase in maritime traffic using unreliable nautical charts and navigation publications increases potential maritime accidents and incidents. Guided by that assumption, the number of stranded ships was analysed. The conclusions of the risk depending on the region were calculated. The obtained findings confirmed the relationship between the number of stranded ships and areas with the inadequately conducted hydrographic survey. IHO regions D, F, and K have 50 % of all strands in the observed period. Namely, zone D has almost 50 % of its area under 200 m inadequately surveyed, and regions F and K are those regions whose data are missing from IHO C-55 publication and are not available for analysis. Such results indicate the accuracy of the assumption that the coverage of areas with an adequate hydrographic survey is even smaller than what is presented in C-55 publication and that maritime safety is strongly compromised in these areas.

The disparity between regions was identified as the IHO divides the world into 15 regions. It was evident that some regions have a very large coastline and sea surface to be surveyed. Hence, the coastline and sea surface by the IHO regions became the novel parameters to be determined. Until now, the mentioned parameters have not been calculated by regions. These calculations were performed using the QGIS. The highest values of the investigated parameters depending on the IHO regions were calculated and analysed and then compared to the areas with no hydrographic survey. It is concluded that the IHO region L with the largest sea surface and with one of the longest coastlines has the highest percentage of no surveyed areas. This region has 12 % of the depths shallower than 200 m unsurveyed, with the percentage rising to 21 % of unsurveyed areas for the depths greater than 200 m. Based on the obtained results, it is concluded that the coverage of an adequate hydrographic survey is inversely proportional to the coastline length and sea surface by each IHO region. The obtained results confirm the validity of the calculations and analysis of the novel parameters in the context of the coverage of the hydrographic survey.

Firstly, it has to be pointed out that hydrographic surveys are performed in different survey areas. Further, each hydrographic survey area has an abundance of features to be considered. Also, all technologies are not suitable for every area. Hence, their performances are not universal and depend on the manufacturer, model, components, etc. Otherwise, the overall budget, urgency, and accuracy play an essential role. For example, some areas require an urgent hydrographic survey, and then most often, the increase in implementation speed decreases the accuracy. Therefore, in addition to finding suitable technology for the survey area, the selected technology must satisfy the required hydrographic survey criteria.

The main contribution of this research and this thesis is the development of the hydrographic survey optimal technologies' selection model. It has to be emphasized that the proposed method can be applied to all survey areas and all available technologies. Furthermore, it is also necessary to point out that criteria (e.g., accuracy, budget, time) should be included in the process of an optimal selection. Original scientific contribution is composed of a reduced binary elimination matrix as a first step in the process of choosing the optimal hydrographic technologies. The matrix is the novelty and represents the input in the decision tree model. The decision tree model represents the second step as one of the supervised machine learning techniques for inducing a decision from training data. The Weighted Sum Model is used as one of the multi-criteria optimization methods that combine computational and mathematical tools to assess the performance criteria by decision makers. Finally, it has to be noted that at present there are no similar developed algorithms from the available literature.

The first step involves the obtained hydrographic survey area data. These are the primary data that the surveyor needs before surveying (such as min/max depth, seabed type, etc.). A reduced elimination binary matrix contains the distribution of characteristics and sub-characteristics of a hydrographic survey area to facilitate data management. It has to be pointed out that this matrix is the novelty of the proposed methodology and represents the input in the model. However, it is generally applicable and can be supplemented with new data as needed and assessed by a hydrographer. It has to be highlighted that the purpose of the matrix is to select suitable technologies that may be taken for further consideration with respect to the characteristics of the survey area. The performances of the technologies are available from the manufacturer. Given all the access data, the hydrographer has a simple task of binary filling the matrix. The most significant purpose of the matrix is to make a decision tree based on the binary data from the matrix.

The primary function of a decision tree is to create a model that can predict all possible alternatives. Then, suitable technologies are further eliminated and graduated given their performance and required hydrographic survey quality.

From the above discussion about the elimination matrix and a decision tree model, it is evident that the created decision tree model is done once. Also, if a new technology becomes available and has different performances, it requires a new tree to be made.

The applicability and validation of the proposed method are shown in the proposed study case. Kaštela Bay represented the hydrographic area of interest. The binary values in the elimination matrix indicate the suitability of using all observed technologies concerning hydrographic survey characteristics of Kaštela Bay. Based on the results of the matrix, SBES (research vessel), SBES+SSS (research vessel), MBES (research vessel), MBES (research vessel)+SBES (small boat), LIDAR (UAV), SDB (satellite sensors) were the appropriate technologies.

The binary data from the matrix represent an input for a decision tree model. The decision tree model confirmed, from the reduced binary elimination matrix, that all observed technologies are suitable for hydrographic surveys in Kaštela Bay. Hence, all observed technologies are taken as available alternatives for choosing the optimal technological solution for Kaštela Bay.

Following the above discussion, the multi-criteria decision-making is performed by three criteria: cost, accuracy, and urgency. First, the cost was selected as the preferred criteria for the study, then the criterion of accuracy follows, and the least important measure is urgency for Kaštela Bay study case. Further, by applying WSM, the numerical results which have ranked technologies for the hydrographic survey are obtained. The optimal technology for Kaštela Bay study case was MBES (research vessel) and MBES (research vessel) + SBES (small boat) with a score of 0.97. Then with a score of 0.82 follows the SDB technology. Other available alternatives have a significantly lower score. It is a small evident difference between the three alternatives SBES (research vessel), SBES+SSS (research vessel), and LIDAR, which have a WSM score in the range from 0.58 – 0.65. These numerical results suggest that the mentioned alternatives will not be taken for the observed hydrographic survey area. With this approach, it is possible to look at all available alternatives and all criteria concerning some areas and realistically decide on the optimal technology.

Furthermore, if the costs were the only decision criterion, after applying the proposed algorithm, only the cheapest alternative would be selected as the best technology, which may not be as efficient and effective as other technologies. Hence, such an approach would represent a constraint in practice. Therefore, it is not recommended to select optimal technologies to be guided solely by cost as the only decision criterion. The time factor is also considered to be an important criterion in a hydrographic survey and holds the second place in importance and has to be included in a multi-decision optimization.

Generally, the following parameters have to be highlighted: parameters that represent the input to the model are the reduced binary elimination matrix and the optimization criteria. Also, the binary matrix is obtained based on available data of the survey area and available technologies. Further, optimization criteria are determined based on the financial budget, the time available, and the desired level of accuracy. Finally, all mentioned elements in the matrix and optimization criteria are filled by a hydrographer using the proposed methodology and available data.

Future research includes other multi-decision methods that could be investigated on this subject. Also, it is necessary to compare them to reach a conclusion on the most appropriate. Further, ongoing research will include researching the practical feasibility of the automated system of the proposed methodology. Figure 7.1 could be a basis for the automation algorithm of ongoing research.

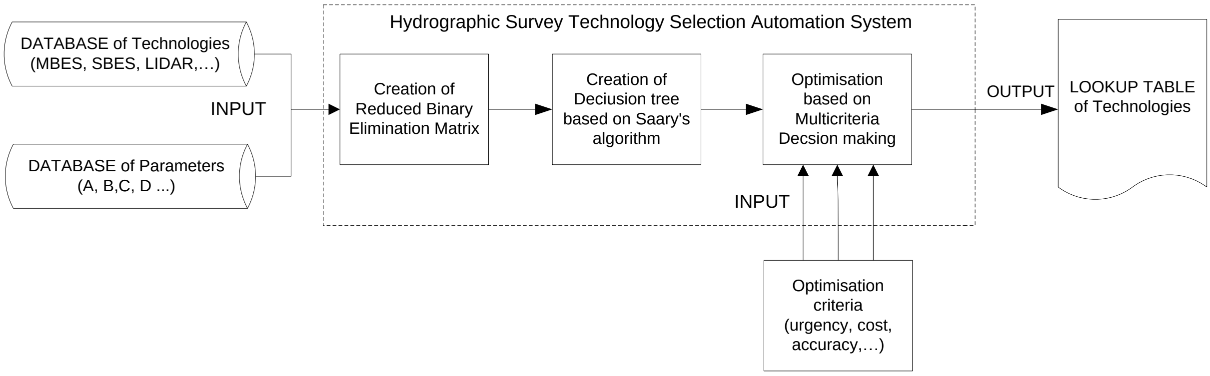


Figure 7.1 The automation algorithm

Figure 7.1 shows the proposed hydrographic survey technology selection system. It consists of several inputs and one output. Input parameters are divided into input parameters for a reduced binary elimination matrix and input parameters for optimization criteria. The output of the proposed automated system is a lookup table. The table contains a list of all included technologies ranked from the most suitable to least suitable.

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11. BIOGRAPHY

Ivana Golub Medvešek was born in Split, on November 28, 1983. She is married and a mother of four children. After finishing primary education, she completes IV. General high school "Marko Marulić" in Split. She continued her education enrolling the Faculty of Maritime Studies in Split in 2002, study of Maritime Systems and Processes. She obtained the title of graduate engineer of maritime transport and nautical engineering in 2007.

Since April 1, 2008, she has been employed as a research assistant at the Faculty of Maritime Studies, University of Split. In the academic year 2009/2010 she continued her education at the postgraduate mutual university scientific doctoral study "Maritime Studies" at the Faculty of Maritime Studies, University of Rijeka. There she continues her education in the scientific field: "Technical Sciences", field: "Transport and Transport Technology" in order to obtain a doctorate of science. After defending the topic of doctoral dissertation at Faculty of Maritime Studies in Rijeka, she transfers to the Postgraduate university study "Technologies in Maritime Affairs" at Faculty of Maritime Studies, University of Split in 2019.

She is fluent in English in speech and writing and is proficient in Italian.

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