TÉCNICO LISBOA

Development of a Multi-criteria Decision Aiding Methodology for Dredging Problems: Analysis of the San Francisco Bay

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Dedication

To my family

Abstract

Maritime transportation is able to carry products for long distance, with low costs and almost unlimited capacity. The development and maintenance of waterways are essential for state owned and private companies that use these courses to be able to compete. The construction and the maintenance of waterways require the performance of dredging activities. These activities consist of the removal of material from the bottom or the side of water channels making them navigable. The USACE (United States of America Corps of Engineers) is responsible for managing dredging activities throughout the USA. It selects and decides the dredging methods, equipment, and disposal alternatives to use. The selection considers environmental, economical, and technological evaluations. However, there is no formal method to select the most adequate machines. Thus, this Dissertation intends to be a first contribution for the development of an MCDA methodology to rank the dredging machines according to their adequacy for a given scenario. To achieve these goals it firstly presents general information about dredging activities, particularly, in the USA. Secondly, it provides, a literature review, focused mainly on the application of MCDA approaches to similar case studies. Finally, it introduces the main steps for the construction of the methodology and presents the results of its application to the San Francisco Bay port. This Dissertation is, therefore, an introduction to the main concerns and problems related with dredging activities. It includes all the steps followed to reach the final model and the results obtained for the San Francisco Bay port.

Key words: Dredging, MCDA, Ranking, USACE

Resumo

O transporte marítimo permite a expedição de produtos por longas distâncias a baixos custos, e tem capacidade quase ilimitada. O desenvolvimento e manutenção dos cursos de água são essenciais para que as empresas que usam este transporte sejam capazes de competir. A construção e a manutenção de vias marítimas requerem o desempenho de dragagem. Estas consistem na remoção de material do fundo e das laterais dos cursos de água tornando-os navegáveis. Nos EUA, o USACE (United States of America Corps of Engineers) é responsável pela gestão das atividades de dragagem. Seleciona e decide, para cada cenário, método, equipamento e local de depósito dos sedimentos que considera mais adequados. A seleção é feita com base em considerações ambientais, económicas e técnicas. No entanto, não existe um método formal de seleção de máquinas de dragagem. Esta Dissertação pretende ser uma primeira abordagem ao desenvolvimento de um Modelo de Avaliação Multicritério com o objetivo de ordenar máquinas de dragagem de acordo com a sua adequação a um dado cenário. Primeiro, é apresentada informação sobre dragagem, particularmente nos EUA. De seguida, é apresentada uma revisão bibliográfica focada na aplicação de abordagens Multicritério a casos semelhantes. Por fim, são introduzidos os passos seguidos na construção da metodologia, bem como os seus resultados quando aplicada ao caso da Baía de São Francisco. A Dissertação é, assim, uma introdução às principais preocupações e problemas relacionados com atividades de dragagem. Inclui todos os passos seguidos, bem como, os resultados obtidos na aplicação à Baía de São Francisco.

Palavras-Chave: Dragagem, MCDA, Ordenação, USACE

Acknowledgment

Writing this Master Dissertation was one of my academic´s biggest challenges. I would not have been capable of doing it without the help of my advisor, co-advisor, family and friends.

I would like to express my gratitude to my supervisor, Professor José Rui Figueira, for all the time and dedication he put in this Master Dissertation. I am truly thankful for all the recommendations, corrections, remarks and continuous support he provided me during the last year. His help was crutial.

I would also like to thank my co-supervisor, Igor Linkov, Ph. D., for allowing me to work with the USACE in this project. A special thanks to Engineers Mathew Bates and Engineer Cate Fox-Lent from the USACE for the hours dedicated to the evaluation of the machines and discussion of the dredging alternatives in the San Francisco Bay port.

Furthermore, I would like to thank my family for all the patience and my boyfriend, Diogo Ribas, for all support and wisdom, which were an inspiration and an example.

Acronyms:

ACFOR – Abundant, Common, Frequent, Occasional, Rare

AHP – Analytic Hierarchy Process

ANOVA – Analysis of Variance

DMMO - Dredged Material Management Office

DSS – Decision Support System

ELECTREE – Elimination and Choice Expressing Reality (ELimination Et Choix Traduisant la REalité)

EPA - United States Environmental Protection Agency

ERA – Ecological Risk Assessment

EW - Environmental Window

FPV – Fundamental Point of View

HIPRE – HIerarchical PREference

MACBETH – Measuring Attractiveness by a Categorical Based Evaluation Technique

MAUT – Multiple Attribute Utility Theory

MAVT – Multiple Attribute Value Theory

MCDA - Multi-Criteria Decision Analysis

MCDM – Multi-Criteria Decision Model

USA - United States of America

USACE - United States Army Corp of Engineers

USD – United States Dollar

USEPA - U.S. Environmental Protection Agency

ProMAA – Probabilistic Multi-criteria Acceptability Analysis

PROMETHEE – Preference Ranking Organization Method for Enrichment Evaluation

SMAA – Stochastic Multi-criteria Acceptability Analysis

SMART – Simple Multi-Attribute Rated Technique

SFBCDC - San Francisco Bay Conservation and Development Commission

SFBRWQCB - San Francisco Bay Regional Water Quality Control Board

VIKOR - VlseKriterijumska Optimizacija I Kompromisno Resenje (VlseKriterijumska optimization and compromise solution)

WA – Weighted Average

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1. Introduction

Dredging is a complex practice with increasing importance all over the world. The performance of dredging activities involves careful and detailed planning to guarantee that the work is done in the most effective and efficient way. Each dredging project is unique, information on the amount and type of material to be dredged is vital for the definition of the best equipment and techniques to be used (USACE, 1983).

This chapter presents the outline of this Master Dissertation including information about the context in which the problem arises, the research methodology that will be adopted, the Master Dissertation´s main goals, the research questions, and the structure that will be followed can be found.

1.1. Contextualization

The growing economic pressure caused by new and powerful economies makes it essential to improve and guarantee competitive solutions that would grant a trading position on the global markets scene. As countries are highly dependent on the import and the export of goods it is necessary to search for cheap ways to transport products for long distances. In most cases maritime transportation is a viable solution because of its almost unlimited capacity, fairly low rates, and abundant route possibilities. It now accounts for 90% of the total volume and 70% of the total value traded (Rodrigue, 2013). Raw materials and finished products travel all over the world in very large ships. These ships require deep waterways to navigate safely. Open oceans are deep enough; however, most ports, harbors, and rivers are not naturally sufficiently deep. It is then vital to increase depth on their critical areas. Dredging activities are performed in order to create new water channels and maintain the existing ones granting that they are deep and wide enough for safe navigation. In Africa, countries such as Angola, Ghana, Namibia, and South Africa are working in the expansion of their ports[1]. Indonesia and The Netherlands are working together in Greater Jakarta in a dredging project involving water safety. In Kuwait the first hydraulic reclamation operation is being performed, showing impressive results. China is using dredging in order to create new and developed already existing structures that guarantee that the high levels of exportations are possible. In North America and Europe several environmental projects are growing showing an increased concern not only with the navigation conditions but also with management of water quality[2].

In the United States of America (USA) these activities are performed by the United States Army Corps of Engineering (USACE). The USACE aims to perform dredging activities in an economical and environmentally preserving manner. Hence, and in order to “optimize” the process, it is necessary to evaluate the characteristics for each site and select the most appropriate set of equipment. It is in this context that this Master Dissertation was originated. The USACE approached Professor José Rui Figueira, from Instituto Superior Técnico (Lisbon), in order to request his help seeking the best solution for its problem. Until now, it has been difficult to establish a methodology for this kind of projects. Professor José Rui Figueira, Dr. Igor Linkov (USACE) and I formed a team to work on the dredging

[1] Consult: www.dredgingtoday.com,
[2] Consult www.dredgingtoday.com

problem statement, in general, and a case study, in particular. Professor José Rui Figueira is my advisor and Dr. Igor Linkov is my co-advisor. For the development of this Master Dissertation we also had the collaboration of Engineer Matthew Bates, Engineer Cate Fox-Lent and Engineer Zachary Collier from the USACE.

The idea is to, formally, compare the available dredging alternatives, also called machines, options, courses of action, or simply actions and to rank them from the best to the worst, and then to select the most viable one taking into consideration aspects such as the technical framework, the type of sediments, the amount of sediments that need to be dredged, and the disposal area.

In what follows, the USACE, represented by Engineer Matthew Bates, Engineer Cate Fox-Lent and Engineer Zachary Collier will be referred as *decision makers* or *clients*, while Professor José Rui Figueira, Dr. Igor Linkov and I will be called *analysts*. The decision makers always work as a team, the opinion express is the result of consensus between them.

The contexts in which dredging activities are developed can vary significantly. Nevertheless, the concerns and the goals are more or less the same: improve water channels with the least possible impact on environment and minimum costs, using the most appropriate techniques.

This problem was addressed using a Multiple Criteria Decision Aiding (MCDA) methodology (Bouyssou *et al.,* 2006). This type of methodology was used in the past in order to deal with other problems concerning dredging, environment, port and harbor development and management. The first step is the representation of the *problem situation* that includes the definition of the actors (stakeholders) involved and their roles as well as their concerns and values, and the resources available. Each actor presents its own concerns: the USACE wants to guarantee that the maximum dredging is done given a limited budget; the environmental agencies want to guarantee that impacts on environment are limited; the fishermen want to guarantee that their fishing conditions will not be affected and the exporters want to guarantee that they will be able to navigate in the water channel.

The second step is the *problem formulation* that translates the decision maker´s concerns into a formal problem. This problem formulation should include a set of *potential alternatives/projects*, a set of *points of view* and a *problem statement*, which anticipates the possible conclusions of the problem. In our case, the result is the ranking of the potential alternatives.

The third step is the *evaluation model*. In this step the information available is organized in order to make it possible to formulate an answer for the problem. The evaluation model is composed by the actual *alternatives* available for comparison and evaluation, the *consequences* regarding each alternative, the *criteria* under which the alternatives are evaluated, the *uncertainty* in the model that can be from both endogenous or exogenous nature and the *aggregation operator*.

The fourth, and final step, is where the *recommendation* is presented to the client. In this phase the conclusions are translated to the client's language and the recommendation is checked in order to ensure that it is technically sound, operationally complete, and legitimated with respect to the decision process.

The methodology here developed was applied to the San Francisco Bay port; however, it intends to be capable of producing results to any future dredging scenario. The identification of a coherent family of criteria (Roy, 1996) is crucial to the global application of the model.

1.2. Research methodology

This section presents the six steps of the research methodology that will be followed in this Master Dissertation. The six steps are:

1) Problem characterization
2) Literature review
3) Model development
4) Model validation
5) Analysis and discussion of the results obtained
6) Final conclusions and future research

The first step – *problem characterization* – presents the description of the problem situation. Here information is provided concerning the generic environment, rules and concerns that should be taken into account when performing dredging activities. Particular importance will be given to dredging in the USA.

The second step - *literature review* - presents information about the application of MCDA and other relevant alternative methods to other problems that are related to the one in study, namely MAUT (Multiple Attribute Utility Theory) and MAVT (Multiples Attribute Value Theory) and outranking. It is also in this section that the main weaknesses of their strategies are identified and an improved methodology is proposed.

The third step - *model development* - includes information about the selection of the methodology and presents the fundamental points of view, criteria and primary scales or metrics.

The fourth step - *model validation* – explains the methodology used, in and applied to the San Francisco Bay port.

The fifth step – *analysis and discussion of the results obtained* - includes the information that results from the application of the methodology developed to the San Francisco Bay port and a sensitivity analysis.

The sixth and final step – *final conclusions and future research* - presents the conclusions related with the methodology and their applications. It also includes recommendations for future research.

1.3. Master Dissertation goals

The investigation in this Master Dissertation will be focused in the application of MCDA for dredging problems more precisely in the USA. It is in this context that the research questions appear, they will be answered throughout this Master Dissertation: What are the main concerns of stakeholders and how to model them? What is the most adequate criteria tree for evaluating dredging problems in the USA? How to characterize the alternatives, machines, and equipment? What kind of results should we produce? What should be the most adequate formal model to produce the results? What kind of recommendations should we provide to the decision maker? In fact, there is a broad research question which groups all of these questions: What is the most adequate MCDA methodology to deal with this kind of project, site, or scenario?

This Master Dissertation main goal is the development of an MCDA *integrated approach* applied to the selection of equipment in dredging problems. Although MCDA has been applied before, some weaknesses to the methodologies commonly used have been found. The methodology here developed intends to be more complete and general enough to be capable of producing useful and applicable results to any dredging site. It was also a concern that the method could be easily reproduced by the USACE later on. For validation the methodology was applied to the San Francisco Bay port. This goal was achieved by following the methodology presented on the previous section.

1.4. Master Dissertation structure

The Dissertation is organized as follows:

- In Chapter 2, information about the problem is presented together with the alternatives in study. The Chapter includes information about the USACE, dredging and disposal operations.
- In Chapter 3, the reader can find the literature review. The literature review is particularly focused on topics related with the application of MCDA and other relevant alternatives to problems related to the one in study. Here strengths and weaknesses of each method/approach are identified and explored.
- In Chapter 4, information about the methodology that is going to be applied is presented. The set of criteria and dimensions that are used in the assessment of the alternatives are presented and explained.
- In Chapter 5 is addressed information about the application of the methodology to the San Francisco Bay port. This chapter includes data about the alternatives and the judgment performed by the decision maker.
- In Chapter 6, the last chapter, the conclusions and results of this Master Dissertation are described. This chapter also includes guidelines for future research in the area.

2. Problem

The present Master Dissertation intends to recommend a methodology to help in the ranking and further selection of dredging machines for operations in the USA performed by the USACE. Particular importance will be given to the available dredging equipment and the aspects that influence their selection. The information provided in this chapter is the result of several conference call interviews with members of the USACE, namely Engineer Matthew Bates, Engineer Cate Fox-Lent and Engineer Zachary Collier, in the USA and the reading of Engineering Dredging Manuals and other written sources such as brochures and dredging guides (USACE, 1983) (USACE, 2013). The three decision makers acted as a group, forming for each question a consensual answer. In a first stage, the USACE is introduced, in order to provide information about the setting, where the problem has begun. This is followed by detailed information about the problem; available machines; geographic area of interest; subcontracting; environmental concerns; disposal alternatives; and economic constraints.

2.1. Introduction to the United States Army Corps of Engineers

The USACE is a USA Federal Agency, created in 1755 and established independently in 1802. Since its foundation it has contributed actively in all American wars constructing infrastructures in the USA and abroad. However, its responsibilities include not only military constructions but also civil services. In the 19th and 20th century the importance of USACE as a provider of civil support has grown significantly. The jobs performed by then included fortification of the coast, elimination of navigation hazards, construction of lighthouses, jetties and piers for harbors and mapping navigation channels. At the same time, the USACE was also responsible for the control of water resources, maintenance of public construction, and support to military activities. In the world, the USACE works in more than 130 countries. Over 200 years after the foundation the USACE has now a staff team of around 37 000 civilians and soldiers working in peace and war environments. They are responsible for granting conditions for the economy to prosper, granting security, and help in the prevention of natural disasters. All the activities performed by the USACE are in line with the preservation and restoring of the USA´ environment.

2.2. Problem description

One of the most important missions of the USACE nowadays is to dredge, that is to perform underwater excavation. Dredging is used to guarantee safe navigation on the waterways. Ships of increasing size have to be able not only to circulate on Open Ocean but also on harbors, ports and rivers, most of which not naturally deep enough. Between 250 and 300 million cubic yards of sediments are dredged every year in the USA. (Suedel *et al.,* 2008)

Each dredging project should be performed in an efficient, cost-effective, and environmental acceptable manner in order to improve and maintain the USA waterways and allow, among other activities, safe navigation (USACE, 1983). There are two types of planned jobs in dredging, new projects in areas that have never been dredged before and maintenance dredging in areas that have been dredge before and where the effect of nature requires periodic repetition of dredging. Therefore, when performing dredging activities both short and long term scenarios have to be considered.

Before any dredging activity is performed and in order to obtain crucial information the USACE requires that some steps are followed. The first consideration is the dredging location and the quantities of material to be dredged taking into account both short and long term needs. Secondly, information about the sediments is require; namely it is necessary to determine the physical and chemical characteristics of the sediment. Once the sediment has been analyzed, it is important to consider the disposal alternatives available. After that, social, environmental and institutional factors are identified. The last step is the evaluation of the dredge plant requirements.

The selection of the best dredging equipment and method requires the consideration of several aspects, namely:

1. Physical characteristics of the sediments;
2. Quantities of sediments that need to be dredged;
3. Depth required in the given area;
4. Distance between the dredging and the disposal site;
5. Physical environment on the different scenarios (dredging area, disposal area, areas in between);
6. Level of contamination;
7. Disposal method;
8. Types of dredges available.

Although all the decisions about the dredging works are made by the USACE, there is also space for the local authorities, fishermen, and other interest parties to express their concerns. In terms of environmental regulation, the USACE has its own agency. The USA has national environmental laws and State´s environment laws that can differ significantly. The environmental agency should guarantee that for each dredging work all norms are followed (USACE, 1983).

2.2.1. Available Machines

There are three main types of machines operating in the USA: hydraulic pipeline (cutter-head, dustpan, plain suction and side-caster), hopper dredges, and clamshell dredges.

The dredging is therefore done by three different mechanisms: suction dredging (usually used for maintenance dredging projects - it works better with loose material), mechanical dredging (used in new or maintenance projects - it works with both loose and hard sediments) and a combination of suction and mechanical dredging (USACE, 1983). The USACE´s machines are placed in several USA Districts for planed dredging activities, emergency situations and USA´ national defense.

Hopper dredges are self-propelled ships, which means that the dredging equipment is included in the vessel. The operation of this type of equipment starts with the use of a pump to raise the sediments that are then stored in the hoppers of the ship. Throughout the entire process the ship is always moving.

The disposal can be done by simply open of the doors in the hopper, in open waters, or by pumping the sediment to an upland location. Open water disposal has seen its popularity decrease significantly due to environmental considerations. Because the equipment is easily maneuvered, it is frequently used in sites subjected to intense traffic. The list of advantages and limitations of this equipment can be found on Table 1.

Table 1 - Hopper dredges, advantages and limitations

Machines	Advantages	Limitations
Hopper dredges	Safe, effective and economical in open water	Cannot work continuously
	Can move itself to the dredging location fast and economically	Not very precise
	Can work without traffic perturbation	Less economical when some dredge sediments are contained
	Can provide almost immediate results	Inappropriate to dredge banks of hard packed sand
	Most economical when disposal areas are not available within economic pumping distances of the hydraulic pipeline dredge	Inappropriate to dredge around piers and other structures
		Cannot dredged consolidated clay economically

The **cutter-head dredges** are the most commonly used option in the USA due to their efficiency and capacity to adapt. The dredged material can be disposed in open water directly by the cutterhead or using hopper barges or it can be disposed in confined disposal areas.   The list of advantages and limitations of this equipment can be found on Table 2.

Table 2 - Cutter-head dredges, advantages and limitations

Machines	Advantages	Limitations
Cutter-head dredges	Can excavate a wide range of materials and pump it through pipelines for long distances	Limited capacity for open-water sites, it cannot work with waves more than 0,6-1 m high
	Can work in almost continuous dredging cycles	Cannot move by itself
		Inadequate for dredging medium and coarse sand in maintaining open channels in sites with rapid currents
		Can cause difficult traffic situations when working on small or particularly busy harbors

The **dustpan dredge** is a hydraulic method developed by the USACE. The idea was to create equipment that could excavate efficiently in shallow water. The disposal is in general done in adjacent open waters. Because it is capable of travelling long distances fast, it is a common choice for emergency situations. The list of advantages and limitations of this equipment can be found on Table 3.

Table 3 - Dustpan dredges, advantages and limitations

Machines	Advantages	Limitations
Dustpan dredges	Self-propelled	Can only dredge material like sand and gravels
	Possible to assemble quickly	The disposal site needs to be close by
	Can move quickly out of the channel allowing traffic to pass normally	Can only dredge in rivers or sheltered waters

Side-casting dredges were developed to remove material from the bar channels of small coastal inlets. The way of operating is similar to the one of the hopper dredge. However, the side-casting does not have vessels included in the ship, the sediment are pumped directly. Being capable of working with the same sediments as the hopper dredge, the side-casting can dredge in shallow waters.

The **dipper dredges** are particularly adapted for excavating hard and compacted materials, especially in tight places where the easy maneuvering is essential. they are very precise machines. Since there is no possibility of storing the dredged material, dipper dredges have to work close to the disposal area. The list of advantages and limitations of this equipment can be found on Table 4.

Table 4 - Side-casting dredges, advantages and limitations

Machines	Advantages	Limitations
Side-casting dredges	Self-propelled	Requires flotation depths before it can begin to work
	Can immediately start working after travelling to the dredging site	Can only be used in open water
	Can work in shallow or rough waters	Cannot move large volumes of dredged material

The **bucked dredge** uses a bucket to dredge, depending on requirements different types of buckets are selected with different forms and capacities. This type of dredging is particularly adapted to maintenance dredging in materials such as fine-grained sediments. The list of advantages and limitations of this equipment can be found on Table 5.

Table 5 - Bucked dredges, advantages and limitations

Machines	Advantages	Limitations
Bucked dredges	Requires less space to maneuver than other types of dredge	Difficulty retaining soft, semi-suspended fine grained materials
	Can transport material for long distances	Requires scow-type barges to move the material to the disposal site
	Limits the volume of excess water	Does not work well with contaminated sediments
		Low production rate

2.2.2. Geographic area of interest

The USACE performs dredging activities across the USA since 1824. The country´s area is divided into 8 divisions that include 38 districts. In 3 of the 38 districts no dredging activities are performed and not all the districts require permanent dredging activities.

The map below, Figure 1, shows the quantities of jobs performed in each State and the proportion of new and maintenance jobs.

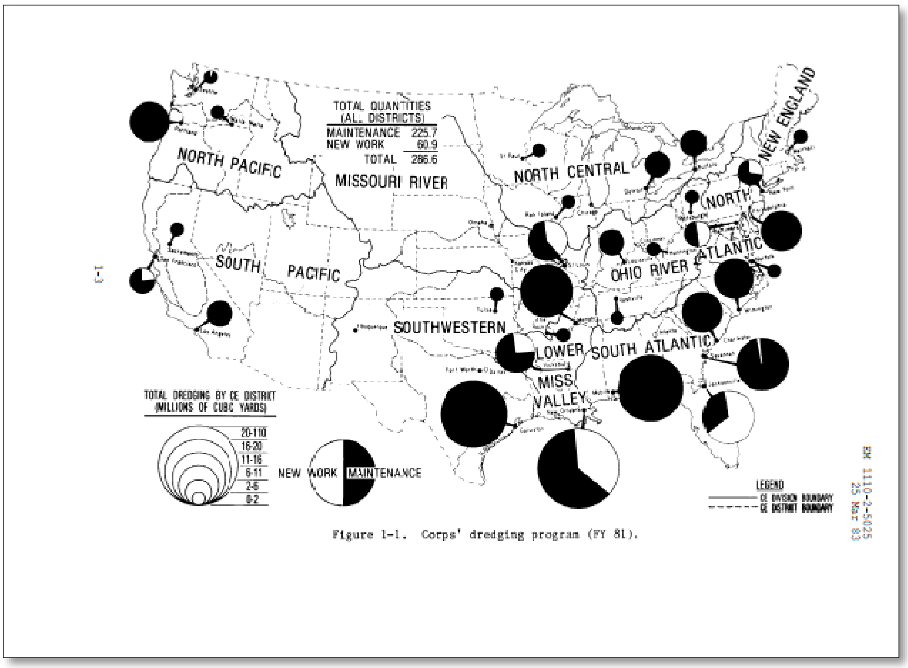


Figure 1 - Map of the dredging activities in the USA (USACE, 1983)

There are three types of jobs performed in the USA, new jobs, maintenance jobs, and emergency jobs. Emergency jobs are non-scheduled needs and can result from hurricanes, floods or storms.

Although the dredging average price per cubic yard is U$5.14 (USACE, 2013) the value is merely indicative. Factors such as the dredge method used, the material dredged, the disposal area and the importance given to environmental concerns make the value vary significantly. The price can go from a little more than U$1 to U$100 per cubic yard. Most of the work is related to maintenance, as the graphs illustrate, new works represents only a small part of total quantity and expenditure.

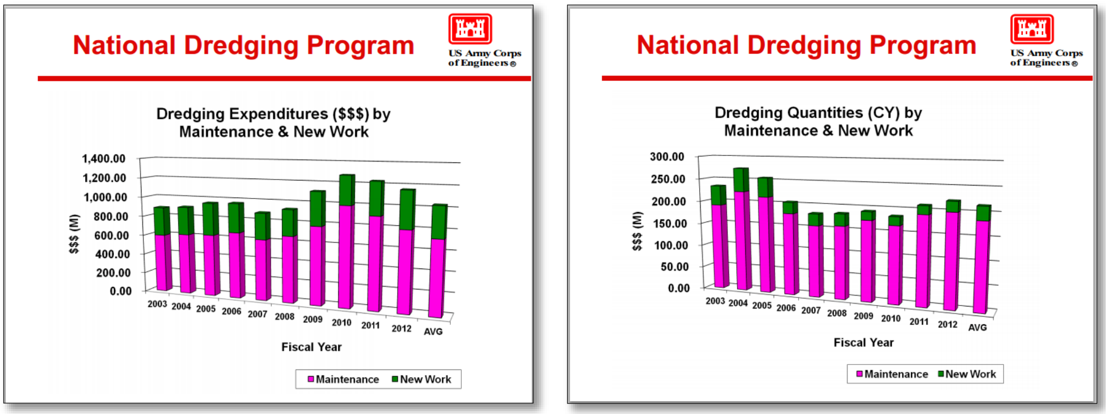


Figure 2 - Dredging Expenditures and Quantities (USACE, 2013)

2.2.3. Outsourcing – Subcontracting

In the USA, the USACE did all dredging works until private companies demanded a free market. Nowadays, in the USA, dredging projects can be performed by the USACE or by private companies.

The private industry demanded in the past that the dredging market should be free; it was its concern that the USACE would do all the projects leaving them with no work. It was in this scenario that the number of machines owed by the USACE started to decrease and the amount of projects outsourced to the private industry increased. The USACE owes now 4 hopper dredges and 6 non-hoppers dredges, a number that is considerably below the country´s needs. Data from the USACE indicates that in 2012 the USACE dredged around 20% of the total sediments, while the private industry did the remaining 80%. Because the USACE maintain the expertise knowledge, even when the work is outsourced, it is still managed by the USACE. Independently of the type of dredging, new work, maintenance or emergency, it is always necessary to develop a contract document. In order to guarantee that the work is being done as contracted and the requirements are being followed, the USACE inspects all the operations. When private entities want to performed their own dredging activities, private ports for example, the USACE has to approve the project, but it has no further influence on the work. Most of the dredging is, as mentioned above, performed by private companies under contract. According to the project, the USACE might demand that some specifications are fulfilled; however this is not usually the case for fair competition purposes. When further specifications are made, they are usually due to environmental concerns.

2.2.4. Environmental Concerns

The physical and chemical characteristics of the dredged sediments can affect the disposal area in the short and in the long term. Most of these effects can be quantified by the amount of clay and organic matter, initial and final pH and oxidation-reduction conditions.

Three methods were identified that can measure the potential impact of the disposal of dredged material in a given site: Water Column Chemistry (which compares the chemical concentration on the water of the disposal site with water quality standards), Total or Bulk Sediment Chemistry (which identifies the resemblances of the sediments that are going to be dredged and the ones on the disposal area), and Bioassay (which measures the effects of the sediments on biological organisms). The water column is affected by chemical contaminants (concentration of manganese, iron, ammonium, nitrogen, orthophosphate, and reactive silica can increase after the disposal) and the turbidity (lack of transparency, usually hard to see by naked eye caused by suspended solids). Because of the proved negative effect of dredging, strategies were developed in order to reduce the impact of these activities whilst considering cost limitations. By studying specific areas, experts are able to understand the behavior of local fauna and flora and discern their fragilities. It was in this context that the Environmental Windows (EW) were created. EWs are periods when dredging activities are allowed due to smaller environmental impact (Suedel *et al.,* 2008). The need to follow these EWs usually results in the inflation of the project´s costs and causes delays.

The selection of the EW depends on four factors: Biological, Physical, Water Quality, and Economic. Each of them is divided in criteria, as showed in the Figure 3.

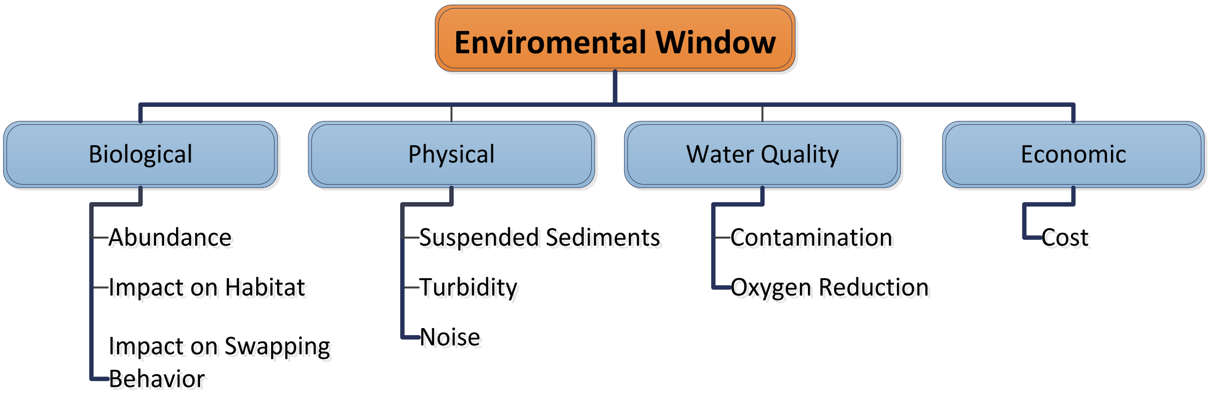


Figure 3 - Criteria for the selection of Environmental Windows

2.2.5. Disposal alternatives

The selection of the disposal alternatives is as important as the selection of the dredging method and depends on economic and environmental factors. The environmental concerns related to dredging activities have also to include the effect of the disposal of sediments (Wilber *et al.,* 2007).

There are three alternatives for disposal: open water disposal, confined disposal, and habitat development. The use of the sediments for the creation of new habitats is limited to non-contaminated sediments. The potential negative impact of chemical and physical characteristics of sediments on the disposal site may be severe. Despite the lack of public support, open water disposal has, in the long term, little effect on the disposal site. Turbidity, for example, only affects a residual amount of species to whom clear water is essential and the concentration of oil and grease on the sediments is not high enough to represent a threat to aquatic species. The biggest inconvenience that comes from this disposal alternative is the transportation of organisms from the dredged area to the disposal site.

Contained area is the second alternative for the dredged sediments. The goal of the contained area is to be able to save the dredged material, whilst allowing the discharge of the water. Just as open water disposal, the contained area carries some environmental consequences, especially in what concerns water and surface contamination. It should be avoided the selection of disposal areas where the levels of contamination after the disposal would imply that the water would no longer be drinkable. Plant population should be used in order to decrease contamination of the soil by metals. Open water disposal and contained disposal are both strongly criticized solutions.

Habitat development seems to be the most consensual option, having in general the support of public opinion. The method has several advantages:

1. The vegetation implanted should be able to fix some of the dredge material preventing it from return to the water;
2. The construction of these new habitats is an opportunity for the development of activities such as sports and fisheries that can in the long term compensate the additional costs;
3. The construction is also an opportunity to develop marshes without great investment.

The structure of the habitat development varies, it can be a marsh, an island, an upland or an aquatic habitat.

2.2.6. Economic Constraints

The USACE, as a Federal Agency, depends on public funding. Part of their one billion dollars budget in 2013 budget was used for the performance of dredging projects (USACE, 2013). Due to current budget limitations not all projects can be undertaken, meaning that in some cases only the most important jobs on major channels are performed. The two types of dredging jobs, navigation and environmental, have very different costs, environmental dredging is significantly more expensive. The first action, the dredging itself, has the same cost for both, navigation and environmental dredging. It is in the disposal activities that the differences show. When performing navigation dredging, the cheaper way to dispose of the sediments is in the closest ocean location possible. Environmental dredging, on the other hand, usually requires a higher cost of handling and transportation to the disposal site.

2.3. Conclusions

Nowadays there is a vast range of dredging options from which machines for a given site can be chosen. In this Master Dissertation and according to the options used by USACE we are going to consider three types of equipment: hydraulic pipeline (cutter-head, dustpan, plain suction, and side-caster), hopper dredges, and clamshell dredges. Each machine and dredging method has its own advantages and disadvantages. There is no universally better machine or technique. The selection, therefore, depends on several criteria. Until now the selection of dredging equipment in the USACE did not follow a formalized approach. Some criteria are not assessed using metrics or they are only depended on an expert´s options. This results on lack of transparency of the process. It is in this context that this Master Dissertation appears. The goal is to develop an integrated approach that would include structuring, modeling and solving the problem. The approach here developed intends to be applied to any dredging equipment and any site. The methodology developed is applied to the San Francisco Bay port problem.

3. Literature Review

Until now the selection of dredging equipment was performed by engineers of the USACE who relied solely on their intuition and previous experience. No formal process was followed. For this selection to become more coherent several methodologies could have been followed, namely optimization and/or simulation based techniques, simple holistic pairwise comparisons of alternatives, or MCDA. Given the amount of data involved in the decision, the multiplicity of sources and categories and the fact that both quantitative and qualitative parameters have to be considered, the selected method must allow not only deal with but also aggregate all types of information. It is also important to guarantee that the selected method performs under conflicting interests. Thus, the selected methodology should be able to produce a model that is perceptible and easily changed as members of the USACE should be able not only to analyze and understand all the output but also be able to adapt the presented model to any other dredging scenario. The only methodology that seems capable of producing the desired outputs and at the same time fulfill all the requirements is MCDA.

The application of MCDA to problems related to dredging, environment or ports, and harbor management is not new. The selection and application of different methods depends on the problem proposed and on the expected results. In the sections below some examples are presented. For each case study, information is given about the goals, approaches and methods used to address problems somehow related with the one we are dealing.

The case studies are organized by category of methodology used. The first section presents case studies in which MCDA was used; it is followed by a section that presents MAUT/MAVT, Outranking and Miscellaneous, and the last section presents case studies in which alternatives to MCDA were selected.

3.1. MAUT/MAVT methods

The first group of examples includes all the situations in which MAUT/MAVT based approaches were used. MAUT identifies the relevant objectives for a given decision and assesses a utility function to all relevant objectives.

Convertino *et al.* (2013) worked in Helsinki in a problem that concerned soil contamination. The goal was to identify the best metrics for design and monitoring of sustainable ecosystems restoration. In order to do so, they followed an MCDA approach based on the application of MAUT and ProMAA (Probabilistic Multi-criteria acceptability analysis). However, as expected, ProMAA proved to be the best method to deal with the problem since it is able to consider probability distribution for weights and utility values of metrics for each criterion. Nevertheless, the results obtained when using MAUT where closed to the ones obtained with of ProMAA.

Critto *et al.* (2007) dealt with a problem related with selection of ecotoxicological tests and ecological observations**.** In order to do so they applied an MCDA approach based on MAUT with DDS-ERAMANIA (Decision Support System for site-specific Ecological Risk Assessment), a software specially developed for environmental risk assessment and experts judgments. This software made it possible for experts and decision makers to easily compare the alternatives and contribute to the selection process. The goal was to rank suitable sets of tests.

Hokkanen *et al* (2000) dealt with contaminated soils in Helsinki. Their goal was to select the best cleaning technology to be used for cleaning polluted soil. In order to do so, they followed an MCA approach based on the application of SMAA-2, a method that analysis what kind of preferences favor each alternative. Before applying SMAA-2, each member of the board defined preferences for each criterion using SMART and ELECTRE III (Elimination and Choice Expressing Reality).

Junior *et al.* (2012) were involved in the creation of solutions for the required improvement in efficiency in the performance of container terminals in Brazil. An MCDA approach was used based on the application of MAVT. The software chosen was MACBETH, which helped in the definition of the weights and in the carry out of the sensitivity analysis.

Pizzol *et al.* (2011) dealt with a problem related with risk assessment for contaminated sites in Upper Silesia, Poland. The goal of this environmental problem was to rank potentially contaminated sites according to their need for intervention. In order to do so, an MCDA was used based on the MAVT. The idea was to develop a flexible method that could be easily adapted to other regions, as well as include the preferences of a group of experts.

Zabeo *et al.* (2011) continued the study started in **Pizzol *et al.* (2011)** working with a problem related with risk assessment in contaminated sites. They were particularly focused on Silesia, Poland. The goal was to rank contaminated sites based on their necessity for intervention. An MCDA approach was used based on MAVT; this choice was due to differences between attributes, number of attributes and complex relation between them. The results obtained were in line with what was expected by the experts.

3.2. Outranking methods

The second group of examples includes situations in which outranking based approaches were used, for example ELECTREE and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations).

ELECTRE method uses an outranking synthesizing approach and was developed by Bernard Roy in the mid-sixties. This method was followed by other ELECTRE versions and by PROMETHEE (Guitouni *et al.,* 1998).

PROMETHEE works with a finite set of alternatives to be ranked; this method receives attention due to its easy implementation, understandability and stability of results (Al-Shemmeri *et al.,* 1997). PROMETHEE is particularly popular in problems involving Environmental Management (Behzadian *et al.*, 2010).

Alvarez-Guerra *et al.* (2010) worked on the prioritization of sediment management alternatives in the Santander´s Bay. The goal was to rank different areas according to their need for sediment management. With that goal, they followed an MCDA approach based on the application of SMAA and PROMETHEE II. The multiple techniques engaged allowed a higher level of confidence in the results obtained. The work was divided in two phases: first the prioritization of the sediment areas to be dredged applying MCDA, second, the prioritization of the management alternatives using SMAA.

Hermans *et al.* (2007) dealt with the problem related with the management options of the White River Watershed, the goal was to select a set of criteria to evaluate the management alternative and preferences to rank individual and group preferences. In order to do so they followed an MCDA approach based on the application of PROMETHEE II. Before PROMETHEE II was chosen, they considered the use of ELECTREE instead. Stakeholders seemed to find PROMETHEE easier to understand and they were more involved with this method. PROMETHEE also presented more stable results.

Suedel *et al.* (2008) worked in the San Francisco Bay in a problem related with the establishment of environmental windows for dredging operations. The goal was to rank periods according to their environmental impact on the site. In order to do so, an MCDA an approach was applied using SMAA. The software used was SMAA III.

Hokkanen *et al.* (1999) dealt with the selection of the best developing options for the Helsinki harbor having into consideration an environment impact assessment. Using an MCDA approach based on the SMAA method, they intended to rank the alternatives. The problem with their approach was the lack of and the uncertainty related with the information provided, the experts were not always available to collaborate. Nevertheless, all the impacts were evaluated relevant experts.

Al-Rashdan *et al.* (1999) worked in a problem related with the assessment of environmental impacts and ranking of environmental wastewater projects in the Middle East. The goal was to rank environmental projects in the Jordan area. An MCDA approach was used based on PROMETHEE. The graphical representation of the problem allowed by PROMETHEE was particularly important. It was also pointed out as determining the ability of MCDA to deal with conflicting criteria.

Chung *et al.* (2009) worked in a problem related with the prioritization of water management alternatives in Korea. The expected results included a ranking of the alternatives. They used an MCDM approach based on AHP (Analytic Hierarchy Process) and programming on ELECTREE II, Evamix method and Regime method. AHP was used to estimate the weights. It was considered that the ranking of the alternatives instead of the selection of one single optimal solution would be beneficial, since it allowed decision makers to postpone the decision according to new resource constraints.

Abu-Taleb *et al.* (1995) dealt with a problem related with the water resources planning in the Middle East. The problem, whose objective was to rank possible water resources development in the Middle East, was intended to be solved using MCDA. This approach was based on the PROMETHEE V methodology. The result was an optimal subset of options that would guarantee water sustainability.

Tzeng *et al.* (2002) dealt with a problem related with the identification of public preferences and strategies in the Taipei area. The goal was to rank environment quality strategies. An MCDA approach was used based on the application of AHP and ELECTRE III and the ranking method VIKOR. This project had to combine the opinion of the residents with the judgments of experts.

Semenzin *et al.* (2007) worked in the development of a site-specific Ecological Risk Assessment for contaminated sites. The goal was to create and rank a set of bioavailability tools to be applied in each tier of the TRIAD, no specific site was considered. In order to do so, an MCDA approach was used with DDS-ERAMANIA software. This software enables decision makers to add more experts´ judgments or alternatives that can improve the quality of the ranking.

3.3. Combination of multiple MCDA methodologies

In the literature found multiple MCDA methodologies were used to deal with the same problem. Methodologies that belong to different families were used in each of the case studies presented below.

Alvarez-Guerra *et al.* (2009) dealt with a problem related to the prioritization of sediment management in the Bay of Santander, Spain. The objective was to rank different areas, according to their need for sediment management. They followed an MCDA approach based on the application of MAUT, AHP, ELECTRE and PROMETHEE.

Yatsalo *et al.* (2007) dealt with the assessment of different contaminated sediments in the New Jersey/ New York harbor and Cocheco River Superfund Site in New Hampshire. The goal was to select the best management options for the contaminated sediments for both sites. In order to be able to evaluate the strengths and the weaknesses of each technique, the application of the MCDA approach was based on both MAVT, AHP and outranking (PROMETHEE) with the corresponding software CritDecPluc, ExpertChoice and DecisionLab. The rankings obtained for the two case studies varied according to the technique used. The authors highlighted the advantages of using multiple techniques since that leads to a deeper understanding about the problem.

Félix *et al.* (2012) worked in Spain in a problem related with the management solution to control the erosion in Granada caused by the construction of a dam. The goal was to rank management alternatives. An MCDA approach was used based on the SMAA-2 method. This choice was based on the capacity of this method to deal with a situation in which criteria values or preferences are unknown.

Marttunen *et al.* (1995) worked in a project that had as a goal the creation of an MCDA model that could be used in the assessment of environmental impacts. In order to do so, AHP and SMART techniques were applied together with the software HIPRE 3+. As a result of this project, a useful tool that can implement decision analytical methods was created.

Mahmoud *et al.* (2000) addressed a problem related with the possible management alternatives for the Sacramento River, California. The goal was to rank alternatives for andromodous fish migration through the dam. To solve this problem, an MCDA approach was used. Five MCDMs (Multi-criteria Decision Methods) were used: Weighted Average (WA), PROMETHEE II, Compromise Programming, ELECTRE II and AHP. The methods were then ranked by the consistence of the results, amount of iterations required and the degree of usability. The results showed the advantages and disadvantages of each method, no method was considered universally superior.

The case studies presented are examples of the diversity of techniques that can be used to solve a problem involving MCDA. These decision processes allow the decision maker to understand his or her preferences and the set of available alternatives (Henig *et al.,* 1996). Multi-criteria Decision Aiding works with three types of decision problems: ranking, sorting, and choice (Corrente *et al.,* 2013).

There is no universally superior MCDA method (Guitouni *et al.,* 1998); each method has its own weak and strong points (Al-Shemmeri *et al.,* 1997), the choice of the best method depends on the problem.

Most authors presented the same set of reasons to use MCDA: the capability to rank or select alternatives even when there are conflicting criteria and the possibility of aggregating data from different sources. Indeed it is capable of producing results even when the information is not perfect. MCDA is also useful to high light missing information. Of course, when more information is available the uncertainty related with the proposed solution is reduced.

The biggest weakness found on the previous case studies was the lack of consistency. It was common to find papers in which several unrelated techniques were used. For example, it is hard to make sense of simultaneously use of an outranking and MAUT/MAVT for the same problem, as the nature of the methods is very different. In some cases not all the criteria and fundamental points of view relevant for this type of problems were included in the evaluation.

Moreover, none of the papers seems to present and integrated approach.

3.4. Alternatives to MCDA

The last group of examples includes situations in which optimization, simulation based techniques or simple holistic pair wise comparison were used. While the first pair of examples regards simulation, the second regards optimization techniques.

Capello *et al.* (2014) worked with a problem concerning the spread of the dredged sediments. Their goal was to be able to produce a numerical three dimensional model that would simulate the sedimentation process. In order to do so, a Lagragian trajectory was used. This type of trajectory is commonly applied in projects related with fluid dynamics. The results obtained are particularly relevant to predict the concentration and distribution of sediments in future dredging sites.

Zhong *et al.* (2010) dealt with a problem concerning the denitrification in sediments in Meiliang, China. The goal was to identify the effects of dredging in the denitrification in sediments. This goal was reached by simulating in laboratory the conditions that could be found in nature. The data that resulted from the simulation was analyzed with the support of the software SPSS, particularly the one-way ANOVA tool. As a result, they were able to predict the expected negative effects in the sediments in terms of denitrification before the dredging was performed.

Estrada *et al.* (2009) dealt with a problem related with the determination of policies that would improve water quality. They were particularly interested in the eutrophication process. The goal was to create an optimization model, the objective function would be minimized and represent the difference between the measured concentration of phytoplankton and the desired concentration. According to the gap between the two values of concentration, a set of policies should be in place.

Knaapen & Hulcher (2002) worked in a project concerning the development of sand waves after dredging. Whenever sand waves block normal circulation of ships on the water channel dredging is performed. After dredging, sand waves tend to reborn with their original shape. The model developed intended to predict and understand the reappearance of sand waves. The goal was reached using a model based on the Landau equation. This case study is an example of the utilization of optimization, more precisely the use of a genetic algorithm.

The examples presented above dealt with problems in which there was only one main concern, being it the simulation of the sedimentation process, the simulation of the denitrification of sediments, optimization of concentration of phytoplankton or the optimization of dredging having into account the development of sand waves. The application of this type of techniques would be harder or impossible if more than one goal was considered.

3.5. Integrated Approach

The application of an integrated approach is the key for the presentation of a unified solution that is able to take advantage of the strongest points of each approach and identify the similarities between them. An approach can be considered integrated if it is capable of integrating the theory and the practice; different MCDA methods.

Here the focus will be on the integration of different methodologies in order to structure, model and define the formal model. This way, robust conclusions for the final recommendations will be presented (Belton *et al.,* 2002).

An integrated approach is not a blind application of several MCDA methodologies that would result in solutions that do not produce relevant information.

No matter the approach followed, the structuring of the decision problem in terms of alternatives and criteria is always done. They all envisage the identification of efficient alternatives, although their way to find them can vary significantly.

In the application of an integrated approach, irrespective of principles and techniques, the methodologies use each other's outcomes as inputs (Belton *et al.,* 2002).

3.6. Conclusions

This literature review is based on the different types of methodologies that can be applied when dealing with a dredging problem.

Some problems can be solved using simulation or optimization techniques, however, due to the wide range of sources of information and the variety of data some can only be solved using MCDA. All these methods are able to deal with great amounts of data and lead to robust conclusions that would contribute to provide recommendations. However, only MCDA is able to aggregate all the different types in one solid recommendation. While MCDA seems to deal with a problem throughout the whole decision process, other techniques seem to work better when confronted with a small slice of a bigger problem. For example, Knaapen & Hulcher (2002) determinate the best timeframe for the development of dredging activities having into consideration the development of the sand waves, although, sand waves are not the only factor that affects the optimal timeframe for the development of dredging activities.

This literature review shows that although MCDA has been used for decades, there is still a lot questions related with the selection of the most appropriate techniques and the application of the techniques selected. Very frequently authors try to overcome the issues related with the selection by applying more than one technique, not necessarily related. This simplification strategy may generate meaningless results. It was also possible to observe from the sample of case studies analyzed the importance of not only applying correctly the techniques but also to have helpful software. The application of an integrated approach seems to be missing in the examples presented. This Master Dissertation intends to overcome this issue by applying an MCDA integrated approach.

4. Methodology

The goal of this Master Dissertation is to develop a multi-criteria model to build a ranking of dredging machines. This chapter presents the steps followed in the construction of such a model. In order to be able to structure the problem it is necessary to define a set of Fundamental Points of View (FPV) that represent major areas of concern; a set of criteria to operationalize these FPV that should be maximized or minimized, and a set of dimensions, from which criteria are built, that include elementary consequences and primary scales or metrics. Since the model will be applied to the case of the San Francisco Bay port, this chapter also includes information about that dredging site.

4.1. Fundamental Points of View

An FPV is a perspective used by the decision maker to analyze the problem (Bana *et al.,* 2005). For the ranking of the dredging equipment, three FPV were created. The first FPV (FPV_1) deals with the negative impacts on the environment caused by dredging activities. The second FPV (FPV_2) will include all the costs and the externalities of a dredging project, positive, and negative cash flows. The third and last FPV (FPV_3) will analyze the technical requirements of the dredging project.

4.2. Criteria

The three FPV are operationalized by a set of seven criteria listed in Figure 4. The first FPV is operationalized by the minimization of the impact on organisms (g_1) and by the minimization of the impact on habitat (g_2). The second FPV is operationalized by the minimization of the dredging costs (g_3) and the maximization of the utility/externalities (g_4). The third FPV is operationalized by the maximization of the adequacy of the equipment to the sediments (g_5), maximization of the adequacy of the equipment to the disposal type (g_6), and the maximization of the adequacy of the equipment to the physical conditions of the site (g_7).

Each criterion is constructed from at least one dimension. Each dimension includes an elementary consequence and a primary scale or metric. The construction of criteria from multiple and continuous dimensions is very difficult and each situations need careful assessment.

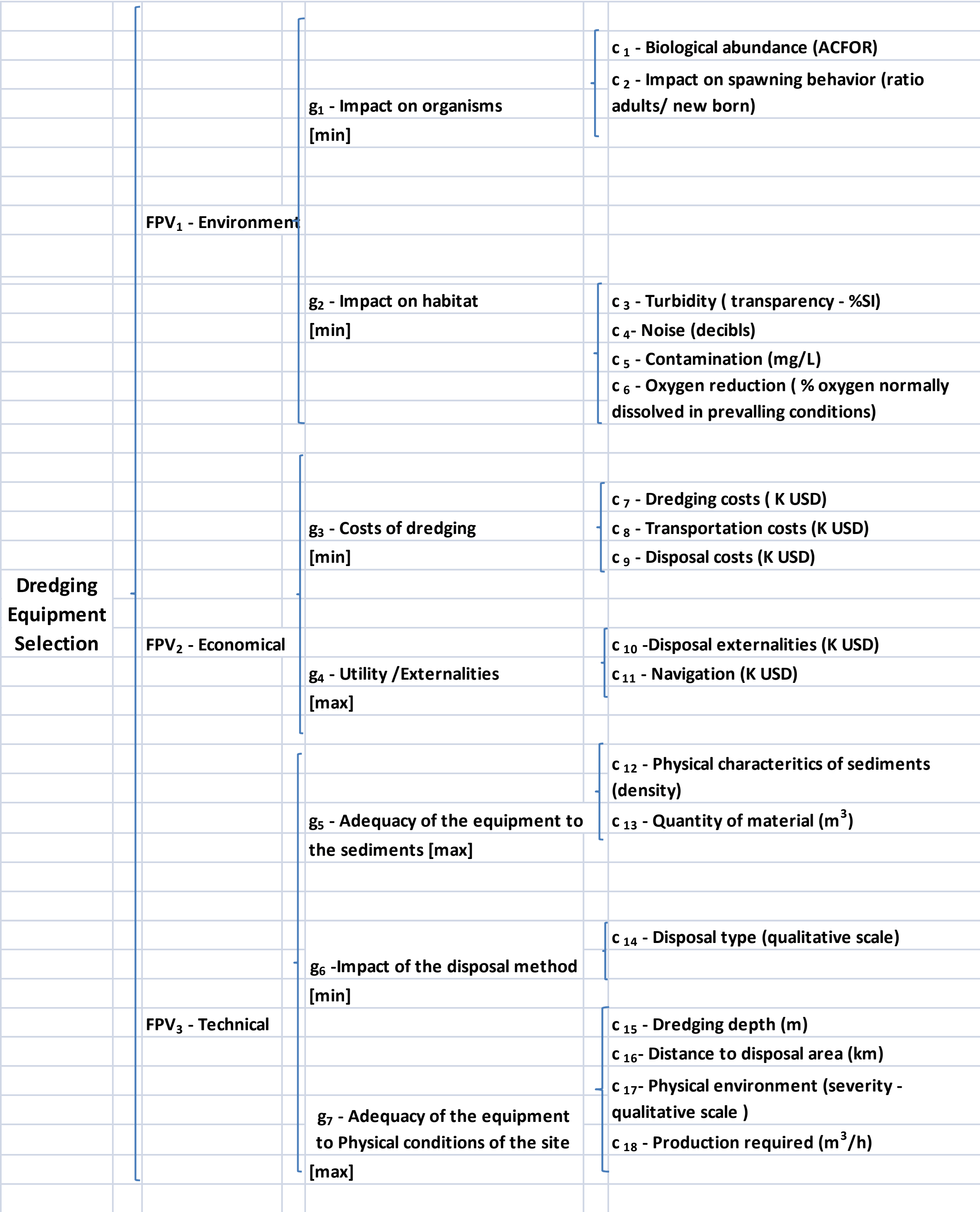


Figure 4 - Criteria tree for the selection of dredging equipment

4.2.1. Impacts on organisms (g_1)

The first criterion is related with the minimization of the impact caused by dredging activities on living organisms. The data required to build this criterion is usually difficult to obtain and the definition of the impact levels is left for the experts´ judgments. Here, two consequences were considered, biological abundance (c_1) and impact on spawning behavior (c_2). For c_1 an assessment process is made by counting the number of individuals from some relevant species present in a sample and comparing this value with the expected value before dredging activities have been performed. In general, each female produces a high amount of eggs that are externally fecundated by males. The changes produced in the environment by the performance of dredging activities might affect the unprotected eggs. One way of testing the impact of dredging activities is to reproduce the agitation conditions in a controlled aquarium.

Biological abundance will be measured according to a qualitative judgment, while the impact on spawning behavior will be assessed, primarily, by a ratio of new born for given species before and after dredging activities are performed, and then, by experts´ judgment.

The considered dimensions, associated with each one of the aforementioned consequences, are the following:

- Dimension 1: The elementary consequence biological abundance (c_1) will be assessed using a purely qualitative 15-levels scale. This scale was constructed by making use of the well-known 5-levels ACFOR scale (hereafter presented from the worst to the best level), $E^1{}_1$ = { k_1^1, k_2^1, k_3^1, k_4^1, k_5^1}, which is applied to measure biological abundance of species in a given area (the acronym ACFOR corresponds to **A**bundant, **C**ommon, **F**requent, **O**ccasional and **R**are):

  k_1^1: Species are **R**are (R);

  k_2^1: Species are **O**ccasionally present (O);

  k_3^1: Species are **F**requent (F);

  k_4^1: Species are **C**ommon (C); and

  k_5^1: Species are **A**bundant (A).

  The level of abundance of a species in a given area is assessed by the experts using the 15-level scale mentioned above. It is assumed that it is worse to switch from a scenario in which the species are occasionally present (k_4^1), to a scenario where species are rarely present (k_5^1) than switching from abundant (k_1^1) to common (k_2^1). The following assortment, Table 6, of 15 levels was constituted, from the most to the least severe:

Table 6 - Levels and labels, dimension 1 (Biological abundance)

Level	Description	Label
l_1^1	The species are abundant (A) before dredging is performed and rare (R) afterwards	AR
l_2^1	The species are common (C) before dredging is performed and rare (R) afterwards	CR
l_3^1	The species are abundant (A) before dredging is performed and occasionally (O) present afterwards	AO
l_4^1	The species are frequent (F) before dredging is performed and rare (R) afterwards	FR
l_5^1	The species are common (C) before dredging is performed and occasionally (O) present afterwards	CO
l_6^1	The species are abundant (A) before dredging is performed and frequent (F) afterwards	AF
l_7^1	The species are occasionally (O) present before dredging is performed and rare (R) afterwards	FR
Table 6 - Levels and labels, dimension 1 (continuation)		

Level	Description	Label
l_8^1	The species are frequent (F) before dredging is performed and occasionally (O) present afterwards	FO
l_9^1	The species are common (C) before dredging is performed and frequent (F) afterwards	CF
l_{10}^1	The species are abundant (A) before dredging is performed and common (C) afterwards	AC
l_{11}^1	The species are rare (R) both in the pre-dredging and post-dredging scenarios	RR
l_{12}^1	The species are occasionally (O) present both in the pre-dredging and post-dredging	OO
l_{13}^1	The species are frequent (F) both in the pre-dredging and post-dredging scenarios	FF
l_{14}^1	The species are common (C) both in the pre-dredging and post-dredging scenarios	CC
l_{15}^1	The species are abundant (A) both in the pre-dredging and post-dredging scenarios	AA

The analysis of the abundance can be performed for a set of species or only for a single species that is considered particularly relevant. When more than one species is particularly important, a comprehensive assessment should be performed and the most suitable level should be assigned. The intervention of a team of experts would, therefore, be essential.

- Dimension 2: The elementary consequence, Impacts on spawning behavior (c_2), will be assessed using a ratio between the numbers of new born of a given species in a given location before and after dredging activities are performed. For each site one ratio will be computed. This ratio, *r*, evaluates the proportion of new born of a given species in a given location that remain after dredging. The ratio is calculated as:

$$r = \frac{number\ of\ new\ born\ of\ a\ given\ specied\ in\ a\ given\ location, after\ dredging}{number\ of\ new\ born\ of\ a\ given\ species\ in\ a\ given\ location, before\ dredging} \quad (1)$$

Ideally the value of *r* should be as close to one as possible. If *r* is equal to one it means that number of new born is the same before and after dredging, no impact on spawning behavior Is verified. The division of the values obtain for *r* into qualitative levels present two problems. The first problem regards the lost of granularity, the division would not guarantee fair attribution of impact levels. The second problem is related with the not linear progression of the severity of losing members of a given species. As so, it was decided that, although the calculation of the ratio represents a valuable input, the final attribution of a level of impact should be done by an expert. For each situation one of the 5- levels scale, $E_2 = \{l_1^2, l_2^2, l_3^2, l_4^2, l_5^2\}$ impact levels should be assigned.

l_1^2: Very severe impact (V);

l_2^2: Severe impact (S);

l_3^2: Acceptable impact (A);

l_4^2: Soft impact (M); and

l_5^2: Very soft impact (L).

The possible levels for the two dimensions of the first criterion should be combined in order to obtain the complete list of alternative for the impact of given equipment in a given site. The condensed version can be found on Table 7, below.

Table 7 - Combination of dimension 1 (Biological abundance) and dimension 2 (Impact on spawning behavior)

		Dimension 2				
		V	S	A	M	L
Dimension 1	AR	V_AR	S_AR	A_AR	M_AR	L_AR
	CR	V_CR	S_CR	A_CR	M_CR	L_CR
	AO	V_AO	S_AO	A_AO	M_AO	L_AO
	FR	V_FR	S_FR	A_FR	M_FR	L_FR
	CO	V_CO	S_CO	A_CO	M_CO	L_CO
	AF	V_AF	S_AF	A_AF	M_AF	L_AF
	OR	V_OR	S_OR	A_OR	M_OR	L_OR
	FO	V_FO	S_FO	A_FO	M_FO	L_FO
	CF	V_CF	S_CF	A_CF	M_CF	L_CF
	AC	V_AC	S_AC	A_AC	M_AC	L_AC
	RR	V_RR	S_RR	A_RR	M_RR	L_RR
	OO	V_OO	S_OO	A_OO	M_OO	L_OO
	FF	V_FF	S_FF	A_FF	M_FF	L_FF
	CC	V_CC	S_CC	A_CC	M_CC	L_CC
	AA	V_AA	S_AA	A_AA	M_AA	L_AA

Dimension 2, due to its long term concern with the replacement of the original conditions, is considered by experts more important than dimension 1, whose concerns are mainly focused on the short term. The combination of dimension 1 with dimension 2 resulted in 75 levels. The levels should be ordered from the strongest to the weakest impact. The ordering was based in one simple rule: levels should be ordered according to the severity of the impact; considering that a two levels change in the impact of dimension 1 is equivalent to one level change in dimension 2.

The 75-levels are presented and described below on Table 8. The labels created are divided into two sets of letters, divided by a dot, the first part corresponds to the level assigned on dimension 1 and the second set correspond to the level assigned on the first dimension.

Table 8 - List of levels and labels criterion 1

Level	Description	Label
l_1	Very severe II abundant to rare	V.AR
l_2	Very severe II common to rare	V.CR
l_2	Very severe II abundant to occasionally present	V.AO
l_3	Very severe II frequent to rare	V.FR
l_3	Very severe II common to occasionally	V.CO
l_3	Very severe II abundant to frequent	V.AF
l_3	Severe II abundant to rare	S.AR
l_4	Very severe II occasionally present to rare	VS.OC
l_4	Very severe II frequent to occasionally present	VS.FO

Table 8 - List of levels and labels criterion 1 (continuation 1)		
Level	**Description**	**Label**
l_4	Very severe II common to frequent	VS.CF
l_4	Very severe II abundant to common	VS.AC
l_4	Severe II common to rare	S.CR
l_4	Severe II abundant to occasionally present	S.AO
l_5	Very severe II rare to rare	VS.RR
l_5	Very severe II occasionally present to occasionally present	VS.OO
l_5	Very severe II frequent to frequent	VS.FF
l_5	Very severe II common to common	VS.CC
l_5	Very severe II abundant to abundant	VS.AA
l_5	Severe II frequent to rare	S.FR
l_5	Severe II common to occasionally present	S.CO
l_5	Severe II abundant to frequent	S.AF
l_5	Acceptable II abundant to rare	A.AR
l_6	Severe II occasionally present to rare	S.OR
l_6	Severe II frequent to occasionally present	S.FO
l_6	Severe II common to frequent	S.CF
l_6	Severe II abundant to common	S.AC
l_6	Acceptable II common to rare	A.CR
l_6	Acceptable II abundant to occasionally	A.AO
l_7	Severe II rare to rare	S.RR
l_7	Severe II occasionally present to occasionally present	S.OO
l_7	Severe II frequent to frequent	S.FF
l_7	Severe II common to common	S.CC
l_7	Severe II abundant to abundant	S.AA
l_7	Acceptable II frequent to rare	A.FR
l_7	Acceptable II common to occasionally present	A.CO
l_7	Acceptable II abundant to frequent	A.AF
l_7	Soft II abundant to rare	M.AR
l_8	Acceptable II occasionally to rare	A.OR
l_8	Acceptable II frequent to occasionally present	A.FO
l_8	Acceptable II common to frequent	A.CF
l_8	Acceptable II abundant to common	A.AC
l_8	Soft impact II common to rare	M.CR
l_8	Soft II abundant to occasionally present	S.AO
l_9	Acceptable II rare to rare	A.RR
l_9	Acceptable II occasionally present to occasionally present	A.OO
l_9	Acceptable II frequent to frequent	A.FF

Table 8 - List of levels and labels criterion 1 (continuation 2)		
Level	**Level**	**Level**
l_9	Acceptable II common to common	A.CC
l_9	Acceptable II abundant to abundant	A.AA
l_9	Soft II frequent to rare	S.FR
l_9	Soft II common to occasionally present	S.CO
l_9	Soft II abundant to frequent	S.AF
l_9	Very soft II abundant to rare	L.AR
l_{10}	Soft II occasionally present to rare	M.OR
l_{10}	Soft II frequent to occasionally present	M.FO
l_{10}	Soft II common to frequent	M.CF
l_{10}	Soft II abundant to common	M.AC
l_{10}	Very soft II common to rare	L.CR
l_{10}	Very soft II abundant to occasionally present	L.AO
l_{11}	Soft II rare to rare	M.RR
l_{11}	Soft II occasionally present to occasionally present	M.OO
l_{11}	Soft II frequent to frequent	M.FF
l_{11}	Soft II common to common	M.CC
l_{11}	Soft II abundant to abundant	M.AA
l_{11}	Very soft II frequent to rare	L.FR
l_{11}	Very soft II common to occasionally present	L.CO
l_{11}	Very soft II abundant to frequent	L.AF
l_{12}	Very soft II occasionally present to rare	L.OR
l_{12}	Very soft II frequent to occasionally present	L.FO
l_{12}	Very soft II common to frequent	L.CF
l_{12}	Very soft II abundant to common	L.AC
l_{13}	Very soft II rare to rare	L.RR
l_{13}	Very soft II occasionally present to occasionally present	L.OO
l_{13}	Very soft II frequent to frequent	L.FF
l_{13}	Very soft II common to common	L.CC
l_{13}	Very soft II abundant to abundant	L.AA

The 75-level list is very extensive. However, it is important to notice that only a part of it will be relevant for each site. For example consider the case in which it was discovered that the San Francisco Bay port scenario is considered to have rare species. This identification of the initial conditions leads us to the conclusion that only 5 out of the 75 levels are relevant for the problem in hands.

Table 9- Possible combinations of dimension 1 (Biological abundance) and dimension 2 (impact on spawning behavior) for the San Francisco Bay

		Dimension 2				
Dimension 1		**V**	**S**	**A**	**M**	**L**
	AR	V_AR	S_AR	A_AR	M_AR	L_AR
	CR	V_CR	S_CR	A_CR	M_CR	L_CR
	AO	V_AO	S_AO	A_AO	M_AO	L_AO
	FR	V_FR	S_FR	A_FR	M_FR	L_FR
	CO	V_CO	S_CO	A_CO	M_CO	L_CO
	AF	V_AF	S_AF	A_AF	M_AF	L_AF
	OR	V_OR	S_OR	A_OR	M_OR	L_OR
	FO	V_FO	S_FO	A_FO	M_FO	L_FO
	CF	V_CF	S_CF	A_CF	M_CF	L_CF
	AC	V_AC	S_AC	A_AC	M_AC	L_AC
	RR	V_RR	S_RR	A_RR	M_RR	L_RR
	OO	V_OO	S_OO	A_OO	M_OO	L_OO
	FF	V_FF	S_FF	A_FF	M_FF	L_FF
	CC	V_CC	S_CC	A_CC	M_CC	L_CC
	AA	V_AA	S_AA	A_AA	M_AA	L_AA

For the San Francisco Bay we will then have eight possible levels, E_{g1} = {V_OR, S_OR, A_OR, M_OR, L_OR, V_OO, S_OO, A_OO, M_OO, L_OO}.

4.2.2. Impacts on habitat (g_2)

The second criterion is related with the minimization of the impact on habitat caused by dredging activities. A total of four dimensions should be considered, turbidity (c_3), noise (c_4), contamination (c_5), and oxygen reduction (c_6). For this criterion the dimensions are all, initially, associated with continuous scales.

In the project of Dissertation, delivered in January 2014, five dimensions were considered. From those, two of these dimensions were: suspended sediments (mg/L) and turbidity (% of surface irradiation). However, during the course of the Master Dissertation a concern was raised regarding the independence of these dimensions, as the amount of suspended sediments has influence in the transparency of the water. In order to correct this situation, the dimension that concerned the suspended sediments was eliminated. In spite of the elimination of one dimension, no important information was left out. Suspended sediments are particularly harmful to the habitats when they are contaminated or when they are in such quantity that prevents normal developments of species in the site, for example due to the lack of sun light. These two major points are included in the dimensions that regard turbidity and contamination.

The information necessary to evaluate the impact of dredging activities on a given habitat is now condensed in four dimensions:

- Dimension 3: Turbidity will be evaluated using the percentage of surface irradiation to measure the water transparency. This metric has a continuous natural numerical value.

- Dimension 4: Noise will be evaluated in decibels. This metric has a continuous natural numerical value.
- Dimension 5: Contamination will be evaluated by the amount of unwanted constituents in the water. It will be measured in mg/L.
- Dimension 6: Oxygen Reductions will be evaluated according to the amount of oxygen available using a percentage of oxygen normally dissolved in prevailing conditions; the metric has a continuous numerical value. It is usually hard to measure the amount of oxygen since it can vary significantly even during the course of a day.

As all the initial scales used for these four dimensions were continuous, it was necessary to develop new scales with a finite number of discrete levels that would allow the construction of the criterion itself. This was done for criterion 1, too. Here, however, the situation was more complex. In fact, since criterion 2 has four dimensions, the number of possible combinations between the levels of each scale is very high. For example, if each dimension is associated with a five-level scale, it would results on five to the power of four, 5^4, or six hundred and twenty five different combinations. The high number of combination adds unnecessary complexity and makes it impossible to perform a full analysis of all the possible combinations. It was then essential to reduce the potential number of combination. The simplification method selected consists in the consideration of only a few key reference impact levels remarkably different for each dimension (Bana e Costa & Beinat, 2005).

If a continuous scale is divided into just two levels, it is impossible to guarantee that the fair level is always attributed to the alternatives. For example, assuming that level one is assigned to machines that have values of performance between 0% and 50% and that level two is assigned to machines that have values of performance between 50% and 100%, if the values of performance are between 49,999% and 51,001%, there is no fair and realistic assignment of levels. To avoid this kind of situation, each assignment should be validated by an expert.

For each scale only two levels were created. Since criterion 2 has four dimensions there are 16 possible combinations. It is expected that the behavior of each alternative is sufficiently different for the criterion to be valuable even with 2-level scales.

For dimension 3, turbidity, the scale created has two levels. Level Av should be assigned to machines whose performance have negligible effect on the transparency of the water and when there is no record, regarding transparency, of impacts on the site. Alternatively, level Lv, can be assigned. This level is attributed when the machine has clear impact on the transparency of the water and it is predictable that this impact will cause damage in the site. Table 10 presents the two alternative levels and labels.

Table 10 - Levels and labels, dimension 3 (turbidity)

Level	Description	Label
l_1^3	acceptable values of water transparency for the site	Av
l_2^3	low values of water transparency for the site	Lv

For dimension 4, noise, the scale created has two levels. Level An should be assigned to all the machines whose performance would lead to acceptable values of noise, meaning that the values of noise verified have no impact on the habitat. On the other hand, if the noise inflict by the machines is sufficiently high to negatively influence the habitat, level Hn should be attributed. Table 11 presents the two alternative levels and labels.

Table 11 - Levels and labels, dimension 4 (noise)

Level	Description	Label
l_1^4	acceptable values of noise	An
l_2^4	high value of noise	Hn

For dimension 5, contamination, the two levels created are Ac, acceptable values of water contamination, and Hc, high levels of water contamination. Level Ac should be assigned when there is no significant change in the degree of contamination. Level Hc should be assigned when the intervention of the dredging equipment causes the contamination of the water in such way that the habitat is in jeoparde. Table 12 presents the two alternative levels and labels.

Table 12 - Levels and labels, dimension 5 (contamination)

Level	Description	Label
l_1^5	acceptable levels of water contamination	Ac
l_2^5	high levels of water contamination	Hc

For dimension 6, oxygen reduction, a two level-scale was created. Level Ao should be attributed when the oxygen levels verified have values that represent low impact on the habitat. Alternatively, level Lo should be assigned whenever the action of the dredging equipment negatively affects the habitat. Table 13 presents the two alternative levels and labels.

Table 13 - Levels and labels, dimension 6 (oxygen reduction)

Level	Description	Label
l_1^6	acceptable levels of oxygen	Ao
l_2^6	low levels of oxygen	Lo

The following tree, Figure5, represents the aggregation of the four previously described dimensions. The new levels, represented in the last row of the tree, are the different levels that could be assigned to dredging equipment and indicate their impact on the habitat. To assess each machine it is necessary to sort the levels from the worst, when the impact is more severe, to the best, when the impact is minimal.

The labels are composed by four letters, each one of them represents the level assigned to each dimension. The first letter is related with dimension 3, the second letter is related with dimension 4, the third letter is related with dimension 5 and the fourth and final letter is related with dimension 6.

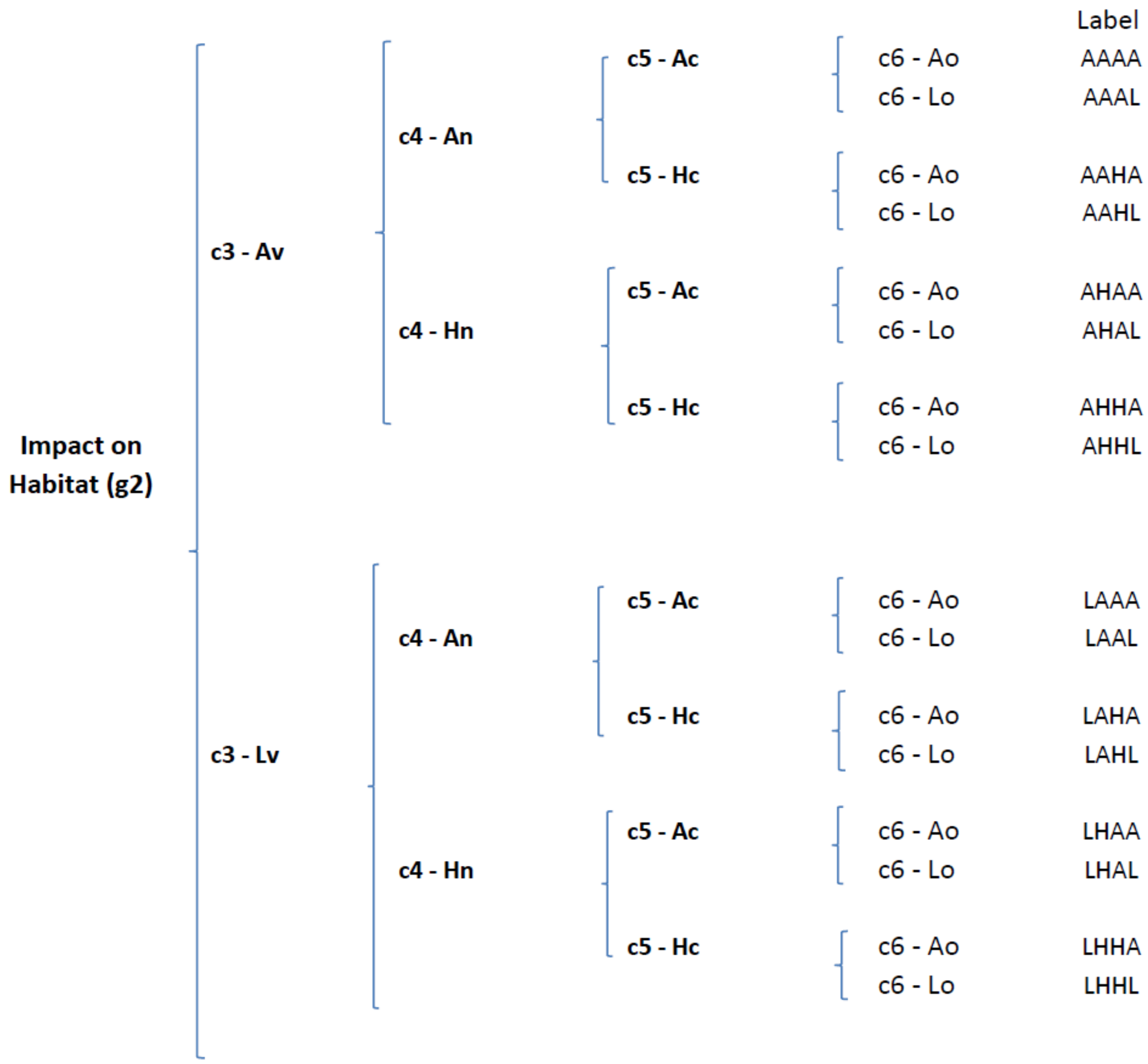


Figure 5 - Criterion tree, criterion 2 (Impact on habitat)

The levels should be ordered according to their severity. For this criterion it was considered that the dimensions were all equally important. Therefore, the least (most) severe scenario would be the one in which the performance of the equipment in all the dimension have the best (worst) result. This assortment is presented on Table 14, below.

Table 14 - Criteria tree, criterion 2 (Impact on habitat)

Level	Description	Label
l_1	Low II High II High II Low	LHHL
l_2	Low II High II High II Acceptable	LHHA
l_2	Low II High II Acceptable II Acceptable	LHAL
l_2	Low II Acceptable II High II Low	LAHL
l_2	Acceptable II High II High II Low	AHHL
l_3	Low II High II Acceptable II Acceptable	LHAA
l_3	Low II Acceptable II High II Acceptable	LAHA
l_3	Low II Acceptable II Acceptable II Low	LAAL
l_3	Acceptable II High II High II Acceptable	AHHA
l_3	Acceptable II High II Acceptable II Low	AHAL
l_3	Acceptable II Acceptable II High II Low	AAHL
l_3	Low II Acceptable II Acceptable II Acceptable	LAAA
l_4	Acceptable II High II Acceptable II Acceptable	AHAA
l_4	Acceptable II Acceptable II High II Acceptable	AAHA
l_4	Acceptable II Acceptable II Acceptable II Low	AAAL
l_5	Acceptable II Acceptable II Acceptable II Acceptable	AAAA

4.2.3. Costs of dredging (g_3)

The third criterion is related with the minimization of dredge costs and has a monetary value measured in K USD (thousands of United States dollars). When dredging activities are performed, there are several costs that should be taken into account: costs of the dredging operations, costs of transportation of the dredged material between the point of dredging and the disposal site, and disposal costs. These costs were translated into a consequence, dredging costs (c_7), transportation costs (c_8), and disposal costs (c_9).

The dimensions are:

- Dimension 7: Dredging costs include all costs associate with the collection of sediments, it will be measured in K USD
- Dimension 8: Transportation costs include the expenses related with the movement of the sediments between the dredging site and the disposal location, it will be measured in K USD
- Dimension 9: Disposal costs include money spent on the operation of disposal, it will be measured in K USD.

Since the dimensions are quantitative and represented in K USD an index should be created (Bana e Costa & Beinat, 2005). An index is constructed in order to combine two or more quantitative dimensions. The advantages of creating an index are the easiness of construction and the possibility to agglomerate the information from the dimensions into one single and meaningful number.

Here, the sum up of expenses made in a dredging project should be made. The expenses made by the equipment should, therefore, are:

$$C_d = Dg + Tr + Di \qquad (2)$$

where:

C_d = Index of costs

Dg = Value of the expenses made in the operation of collecting sediments

Tr = Value of the expenses made in the transportation of the sediments

Di = Value of the expenses made in the disposal of the sediments

The USACE´s dredging budget is, of course, limited and many projects are, every year, left out due to lack of funding. The minimizations of the expenses necessary for each site makes it possible to complete more projects.

4.2.4. Utility or Externalities (g_4)

The fourth criterion is related with the maximization of the utility/externalities, assessed by the value gained with the performance of dredging activities. This value can come from the direct use of new channels or harbors but also from the reuse of dredged materials to create new habitats (limited to sites where the sediments are not contaminated). This criterion is evaluated according to two consequences, disposal externalities (c_{10}) and navigation externalities (c_{11}).

The dimensions are:

- Dimension 10: Disposal externalities include the value gained with the correct disposal of sediments, for example, by creating a new habitat or recreation site, it will be measured in K USD.
- Dimension 11: Navigation externalities includes the value gained by public and private entities from being able to navigate in the waterway, it will be measured in K USD.

The assessment of the externalities´ value is usually hard. Each dredging machine has its own characteristics. These affect the actions that it is able to perform.

For a given dredging project there is a plan that contemplates the expected externalities and costs. It is usually called cost /benefit analysis and the values are presented in K USD. Here it is assessed if the equipment is or is not able to reach those externalities. If the equipment is not able to perform all the actions that would lead to the expected externalities, it would be given a smaller value in this evaluation and if it is able to achieve the goals it would be given a higher value.

Since the two dimensions are quantitative and measured in K USD an index was created. Here, the sum up of the externalities achieved should be made. The externalities achieved by each machine should are:

$$E_d = Dp + Nv \qquad (3)$$

where:

E_d = Index of externalities

Dp = Value of the externalities achieved in disposal

Nv = Value of the externalities achieved in navigation

4.2.5. Adequacy of the equipment to the sediments (g_5)

The fifth criterion is related with the maximization of the adequacy of the equipment for a given type and quantity of sediments. Two consequences were identified: physical characteristics of the sediments (c_{12}) and quantity of material (c_{13}). The dimensions are as follows:

- Dimension 12: Physical characteristics of the sediments are evaluated using the density in kg/m3 of the sediments. Some machines were designed to work with light sediments, while others perform better with dense sediments. The sediments can be considered as not dente, dense or very dense. Category 1, not dense, includes materials such as loss sand and gravel; category 2 includes clay and packed sands; while category 3 includes stone and blasted rock material. The scale of adequacy of the machines to the sediments is divided into 5 levels:

  l_1^{12}: Very bad adequacy;

  l_2^{12}: Bad adequacy;

  l_3^{12}: Acceptable adequacy;

  l_4^{12}: Good adequacy; and

  l_5^{12}: Very good adequacy.

- Dimension 13: Quantity of material that needs to be dredged is indeed assessed in a discreet way. The dimension used is qualitative and discreet. The amount of material can be divided into 4 categories: category 1 includes the scenarios in which a small quantity of material needs to be dredged; category 2 corresponds to the scenarios in which a medium quantity of material needs to be dredged; category 3 includes sites where a high quantity of sediments needs to be dredged; category 4 includes the sites in which a very high quantity of material needs to be dredged. According to their characteristics machines can be more or less adapted. A 5 level scale of adequacy is applied and describing how adequate the equipment is to the quantity of sediments.

  l_1^{13}: Very bad adequacy;

  l_2^{13}: Bad adequacy;

  l_3^{13}: Acceptable adequacy;

  l_4^{13}: Good adequacy; and

  l_5^{13}: Very good adequacy.

The combination of the categories results on 12 different profiles, or types of sediments, as it is shown in the Table 15.

Table 15 - Sediment Profiles

	Physical Characteristics of the sediments			**Quantity of material to be dredged**			
	Not dense	Dense	Very dense	Small	Medium	High	Very high
Profile1	Not dense			Small			
Profile 2	Not dense				Medium		
Profile 3	Not dense					High	
Profile 4	Not dense						Very high
Profile 5		Dense		Small			
Profile 6		Dense			Medium		
Profile 7		Dense				High	
Profile 8		Dense					Very high
Profile 9			Very dense	Small			
Profile 10			Very dense		Medium		
Profile 11			Very dense			High	
Profile 12			Very dense				Very high

The sediments in the San Francisco Bay port are not dense, although very packed, and the amount to dredge is very high. Figure 6 illustrates all possible performances for a specific type of sediments.

			Label
Criterion 5	c_{12} - l_1^{12}:Very bad adequacy	c_{13} - l_1^{13}:Very bad adequacy	VbVb
		c_{13} - l_2^{13}:Bad adequacy	VbB
		c_{13} - l_3^{13}:Acceptable adequacy	VbA
		c_{13} - l_4^{13}:Good adequacy	VbG
		c_{13} - l_5^{13}:Very good adequacy	VbVg
	c_{12} - l_2^{12}:Bad adequacy	c_{13} - l_1^{13}:Very bad adequacy	BVb
		c_{13} - l_2^{13}:Bad adequacy	BB
		c_{13} - l_3^{13}:Acceptable adequacy	BA
		c_{13} - l_4^{13}:Good adequacy	BG
		c_{13} - l_5^{13}:Very good adequacy	BVg
	c_{12} - l_3^{12}:Acceptable adequacy	c_{13} - l_1^{13}:Very bad adequacy	Avb
		c_{13} - l_2^{13}:Bad adequacy	AB
		c_{13} - l_3^{13}:Accepatble adequacy	AA
		c_{13} - l_4^{13}:Good adequacy	AG
		c_{13} - l_5^{13}:Very good adequacy	Avg
	c_{12} - l_4^{12}:Good adequacy	c_{13} - l_1^{13}:Very bad adequacy	GVb
		c_{13} - l_2^{13}:Bad adequacy	GB
		c_{13} - l_3^{13}:Accepatble adequacy	GA
		c_{13} - l_4^{13}:Good adequacy	GG
		c_{13} - l_5^{13}:Very good adequacy	GVg
	c_{12} - l_5^{1}:Very good adequacy	c_{13} - l_1^{13}:Very bad adequacy	VgVb
		c_{13} - l_2^{13}:Bad adequacy	VgB
		c_{13} - l_3^{13}:Accepatble adequacy	VgA
		c_{13} - l_4^{13}:Good adequacy	VgG
		c_{13} - l_5^{13}:Very good adequacy	VgVg

Figure 6 - Criterion tree, criterion 5

The 25 levels should be ordered according to their severity, from the most to the less severe. The two dimensions are considered equally important, which means that a decrease in the adequacy of one level on dimension 12 is as relevant as a decrease of one level on dimension 13. Some of the combinations presented on the list below, Table 16, have identical performance.

Table 16 - List of levels and labels, criterion 5

Level	Description	Label
l_1	Very bad adequacy II Very bad adequacy	VB.VB
l_2	Very bad adequacy II Bad adequacy	VB.B
l_2	Bad adequacy II Very bad adequacy	B.VB
l_3	Bad adequacy II Bad adequacy	B.B
l_3	Very bad adequacy II Acceptable adequacy	VB.A
l_3	Acceptable adequacy II Very bad adequacy	A.VB
l_4	Very bad adequacy II Good adequacy	VB.G
l_4	Bad adequacy II Very bad adequacy	B.A
l_4	Acceptable adequacy II Bad adequacy	A.B.
l_4	Good adequacy II Very bad adequacy	G.VB
l_5	Bad adequacy II Good Adequacy	B.G
l_5	Acceptable adequacy II Acceptable adequacy	A.A
l_5	Very good adequacy II Very bad adequacy	VB.VG
l_5	Very bad adequacy II Very good adequacy	VG.VB
l_5	Good adequacy II Bad adequacy	G.B
l_6	Bad adequacy II Very good adequacy	B.VG
l_6	Acceptable adequacy II Good adequacy	A.G
l_6	Very good adequacy II Bad adequacy	VG.B
l_6	Good adequacy II Acceptable adequacy	G.A
l_7	Acceptable adequacy II Very good adequacy	A.VG
l_7	Good adequacy II Good adequacy	G.G
l_7	Very good adequacy II Acceptable adequacy	VG.A
l_8	Good adequacy II Very good adequacy	G.VG
l_8	Very good adequacy II Good adequacy	VG.G
l_9	Very good adequacy II Very good adequacy	VG.VG

4.2.6. Impact of the disposal method (g_6)

The sixth criterion is related with the maximization of the adequacy of the equipment to the disposal type. Some machines are mode adequate than others to specific disposal types. This criterion includes only one consequence, method of disposal (c_{14}).

The dimension is:

- Dimension 14: Method of disposal, for this consequence it is very hard to obtain a valid numerical value. For this reason a 5-level scale was developed.

  l_1^{14}: Very bad adequacy;

  l_2^{14}: Bad adequacy;

  l_3^{14}: Acceptable adequacy;

  l_4^{14}: Good adequacy; and

l_5^{14}: Very good adequacy.

This criterion´s scale will be equal to the primary scale associated with the dimension.

4.2.7. Adequacy of the equipment to the physical conditions of the site (g_7)

The seventh and last criterion is related with the maximization of the adequacy of the equipment to the physical conditions of the site.

This criterion was divided in four dimensions, dredging depth (c_{15}), distance to the disposal area (c_{16}), physical environment (c_{17}), and production required (c_{18}).

The dimensions are:

- Dimension 15: Dredging depth is measured in meters (m) and represents the distance between the water level and the depth of the sediments that needs to be dredged. Dredge equipment might or might not be able to dredge at a given depth. This consequence was, therefore, described dichotomously (Yes or No).
  - l_1^{15}: Yes, if the machine is able to work in the given depth; and
  - l_2^{15}: No, if the machine is not able to work in the given depth
- Dimension 16: The distance to the disposal indicates the distance that the ship has to travel between the dredging and the disposal site and it is measured in km. The distances can be categorized into 3 levels: level 1 includes the projects in which there is no need for the equipment to move to dispose the sediments, level 2 includes the project in which a trip of less than 10km is required, level 3 includes projects in which a trip of more than 10km is required. These levels are not mandatory and should only be used when the expert believes they could facilitate the process. For this dimension, one of the 3 following levels should be assigned:
  - l_1^{16}: bad adequacy;
  - l_2^{16}: acceptable adequacy; and
  - l_3^{16}: good adequacy
- Dimension 17: Physical environment severity evaluates how adapted a specific machine is to the water conditions. While some equipment is designed to work in calm water others are capable of working in very turbulent waters. A 3-level scale was created; one of the following levels should be assigned to each machine according to its adequacy to the physical environment of the site.
  - l_1^{17}: bad adequacy;
  - l_2^{17}: acceptable adequacy; and
  - l_3^{17}: good adequacy.

  Level 1, 2 and 3 include projects performed in open channels with rapid current, in open waters, sheltered waters, respectively.
- Dimension 18: Production required is measured in m^3/h. Some equipment produce results faster than others. This consequence is described by a dichotomously scale that indicates if the equipment is able or not to work with the desired efficiency.
  - l_1^{18}: Yes, if the equipment is able to perform the job within the efficiency limit; and

- l_2^{18}: No, if the equipment is unable to perform the job within the efficiency limit

The tree in Figure 7 represents the possible combinations of the consequences.

The procedure used to build this criterion was, as g_5, based on the guidelines to construct multidimensional scales (Bana e Costa *et al.,* 2005).

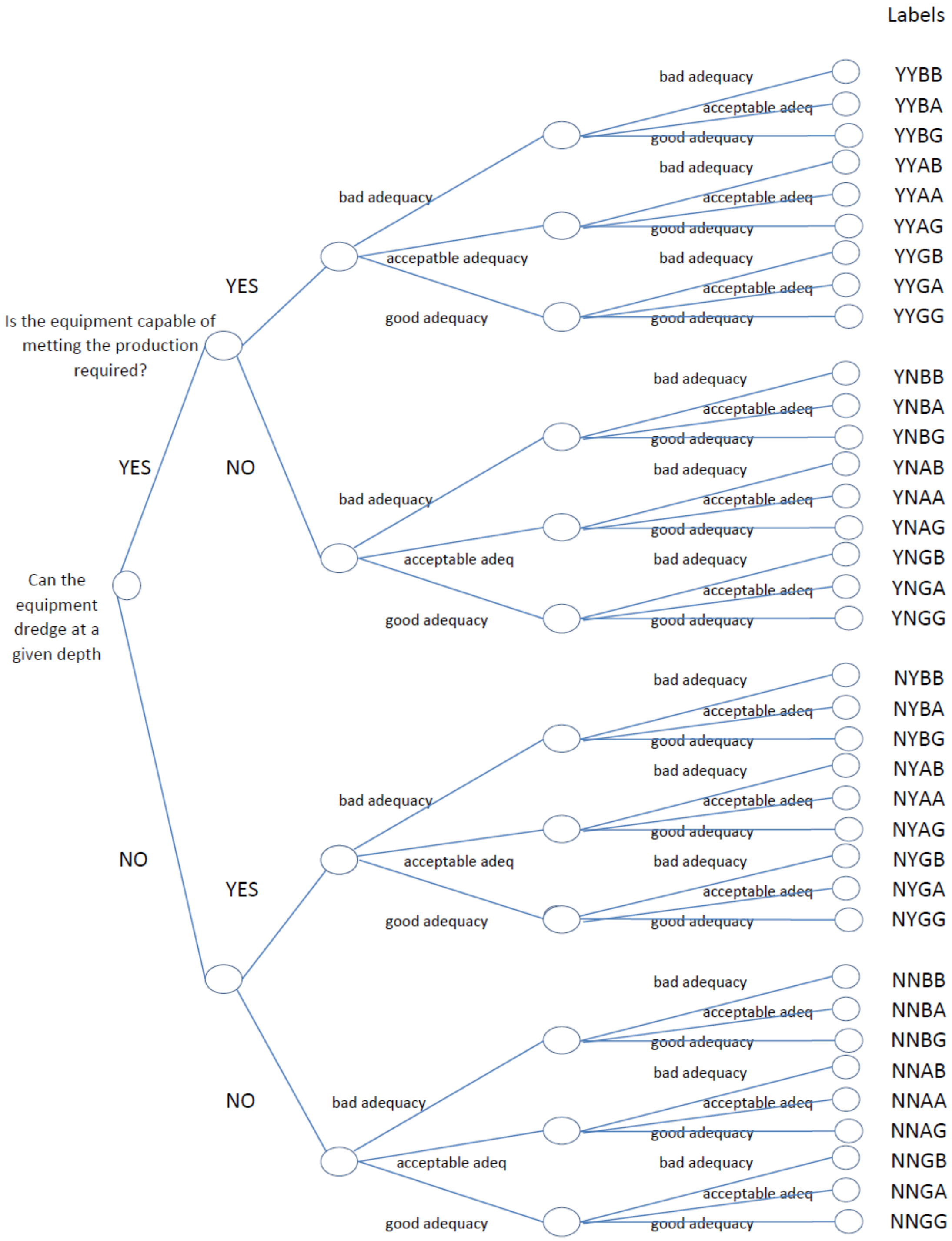


Figure 7 - Construction of the criterion - Adequacy of the equipment to the physical conditions of the site

Table 17 - List of levels and labels, criterion 7 (adequacy of the equipment to the physical conditions of the site)

Level	Description	Label
l_{16}	Yes II Yes II Good adequacy II Good adequacy	YYGG
l_{15}	Yes II Yes II Good adequacy II Acceptable adequacy	YYGA
l_{15}	Yes II Yes II Acceptable adequacy II Good adequacy	YYAG
l_{14}	Yes II Yes II Good adequacy II Bad adequacy	YYGB
l_{14}	Yes II Yes II Acceptable adequacy II Acceptable adequacy	YYAA
l_{14}	Yes II Yes II Bad adequacy II Good adequacy	YYBG
l_{13}	Yes II Yes II Bad adequacy II Acceptable adequacy	YYBA
l_{13}	Yes II Yes II Acceptable adequacy II Bad adequacy	YYAB
l_{12}	Yes II Yes II Bad adequacy II Bad adequacy	YYBB
l_{11}	Yes II No II Good adequacy II Good adequacy	YNGG
l_{10}	Yes II No II Acceptable adequacy II Good adequacy	YNAG
l_{10}	Yes II No II Good adequacy II Acceptable adequacy	YNGA
l_{10}	No II Yes II Good adequacy II Good adequacy	NYGG
l_9	Yes II No II Acceptable adequacy II Acceptable adequacy	YNAA
l_9	Yes II No II Good adequacy II Bad adequacy	YNGB
l_9	Yes II No II Bad adequacy II Good adequacy	YNBG
l_9	No II Yes II Acceptable adequacy II Good adequacy	NYAG
l_9	No II Yes II Good adequacy II Acceptable adequacy	NYGA
l_8	Yes II No II Bad adequacy II Acceptable adequacy	YNBA
l_8	No II Yes II Acceptable adequacy II Acceptable adequacy	NYAA
l_8	Yes II No II Acceptable adequacy II Bad adequacy	YNAB
l_8	No II Yes II Bad adequacy II Good adequacy	NYBG
l_8	No II Yes II Good adequacy II Bad adequacy	NYGB
l_7	Yes II No II Bad adequacy II Bad adequacy	YNBB
l_7	Yes II No II Acceptable adequacy II Bad adequacy	YNAB
l_7	Yes II No II Bad adequacy II Acceptable adequacy	YNBA
l_6	No II Yes II Bad II Bad	NYBB
l_5	No II No II Good adequacy II Good adequacy	NNGG
l_4	No II No II Acceptable adequacy II Good adequacy	NNAG
l_4	No II No II Good adequacy II Acceptable adequacy	NNBA
l_3	No II No II Bad adequacy II Good adequacy	NNBG
l_3	No II No II Acceptable adequacy II Acceptable adequacy	NNAA
l_3	No II No II Good adequacy II Bad adequacy	NNGB
l_2	No II No II Bad adequacy II Acceptable adequacy	NNBA
l_2	No II No II Acceptable adequacy II Bad adequacy	NNAB
l_1	No II No II Bad adequacy II Bad adequacy	NNBB

5. Application

The previous section presented the set of criteria, dimensions, and levels defined for the scales of the model (criteria tree). This information was validated by experts from the USACE. To each available machine seventeen levels were assigned one for each dimension and translated in seven criteria´s levels. This chapter starts with a brief explanation of the procedures used to quantify the differences between levels and its application to the San Francisco Bay port. The performance´s levels assigned to each machine and the corresponding justifications are presented. Moreover, it includes the explanation of the procedure used to obtain the weights of each criterion and its application. To conclude, the scores or values of each alternative are computed and weighted and the different overall scores obtained are compared and ranked. In order to test the robustness of the results and the model a sensitivity analysis was performed. The steps were applied in collaboration with the decision makers team from the USACE, whose involvement was essential.

5.1. Adaptation of the playing cards procedure

Once the different sets of performance´s levels have been identified, the differences between them should be quantified. From the vast range of methods available to do such quantification, it was decided that an adaptation of the revised Simos´ procedure by Figueira and Roy (2002), also called the “playing cards” approach, would be the most appropriate. More precisely,one version of this procedure proposed by Figueira (2014) is used. The following paragraphs are, therefore, based on the paper by Figueira and Roy (2002), where the authors explain the main steps and the computations of the procedure. This option is particularly useful when the decision makers are not familiar with MCDA. The decision makers can easily express their opinion and state in each way they want to rank the sets of performances´ levels. The score of each level is based on this hierarchy. The application of the procedure requires that the decision makers actually use a set or deck of playing cards. The number of cards required varies with the problem at hands; the decision maker should have cards with the name of each level plus a set of white cards that will be used to address the differences in intensity between the different performance´s levels. The procedure can be divided into two phases: the first one consists of the collection of the information, and is performed with the decision maker and the second phase encompasses the computations that would result in the attribution of the score to each element of the set of levels. The majority of the differences between the method originally proposed by J. Simos (1990) and the improved method by Figueira and Roy (2002) appear in the second phase.

Firstly, using the set of cards with the name of each performance´s level, the decision makers are asked to rank the levels in ascending order of importance. This step is presented to test if the scales are well constructed. The first level of the rank should be the one to which the decision maker wants to attribute less value, usually related with more impact or the worst adequacy, and the last level should be the one to which the decision maker wants to assign more importance.

Secondly, the analyst wants to know how much more important one level is when compared with the level that precedes it in the ranking. In this step the decision maker should use the set of white cards. The number of cards assigned to a given difference between two levels should reflect the difference in importance of the two levels the decision-maker feels - a higher number of white cards should be attached when the difference in importance is bigger and a smaller number of white cards should be assigned whenever the difference is small.

If no white cards are assigned to a given difference it means the difference in the scores between the two levels can be used as the unit. If one white card is assigned it means that the difference between the levels is two times the settled unit. If two white cards are assigned it means that the difference between the levels is three times the settled unit. This procedure can be applied with as many white cards as the decision maker wishes.

Once all the white cards have been assigned the information is ready for the second step, the computation of the values. Just like the first step, the second step intends to be easy to apply and replicate.

In the example presented on Figure 8 and Table 18 it was necessary to assigned values to a list of six levels (Bana e Costa *et al.,* 2005). The number of white cards assigned and the corresponding positions are in the Figure. The decision maker was also asked what would be for him a good and a neutral level. Between the level considered good and the neutral one hundred points should be assigned. These points should be assigned equally to each position, zero white cards for one positions, one white card for two positions, two white cards for three positions. The number of positions is equal to one plus the number of white cards.

Assuming that level five was considered good and level two was considered neutral and that between this two levels a total of three white cards, four positions, where attached, then each position corresponds to twenty five points. This results from the division of the one hundred points by the four positions.

To the neutral level, zero points should be assigned, to the good level one hundred points should be assigned. Between level one and level two, one white card was attached or a two positions difference, each position is worth twenty five points, which means that minus fifty points should be attributed to level one.

Level three is one position above level two, which means that it should be worth twenty five points more. The same computation is replicable for each of the remaining levels. The scores for each level are presented on the last column of Figure8.

Table 18 - Example of application of the playing cards´ procedure

Level	Rank	N. of white cards	N. of positions	Points that should be added to the weight of the previous level	Score
	l_6	2	3	+75	175
Good	l_5	1	2	**Good (+50)**	**100**
	l_4	0	1	+25	50
	l_3	0	1	+25	25
Neutral	l_2	1	2	**Base (0)**	**0**
	l_1			-50	-50

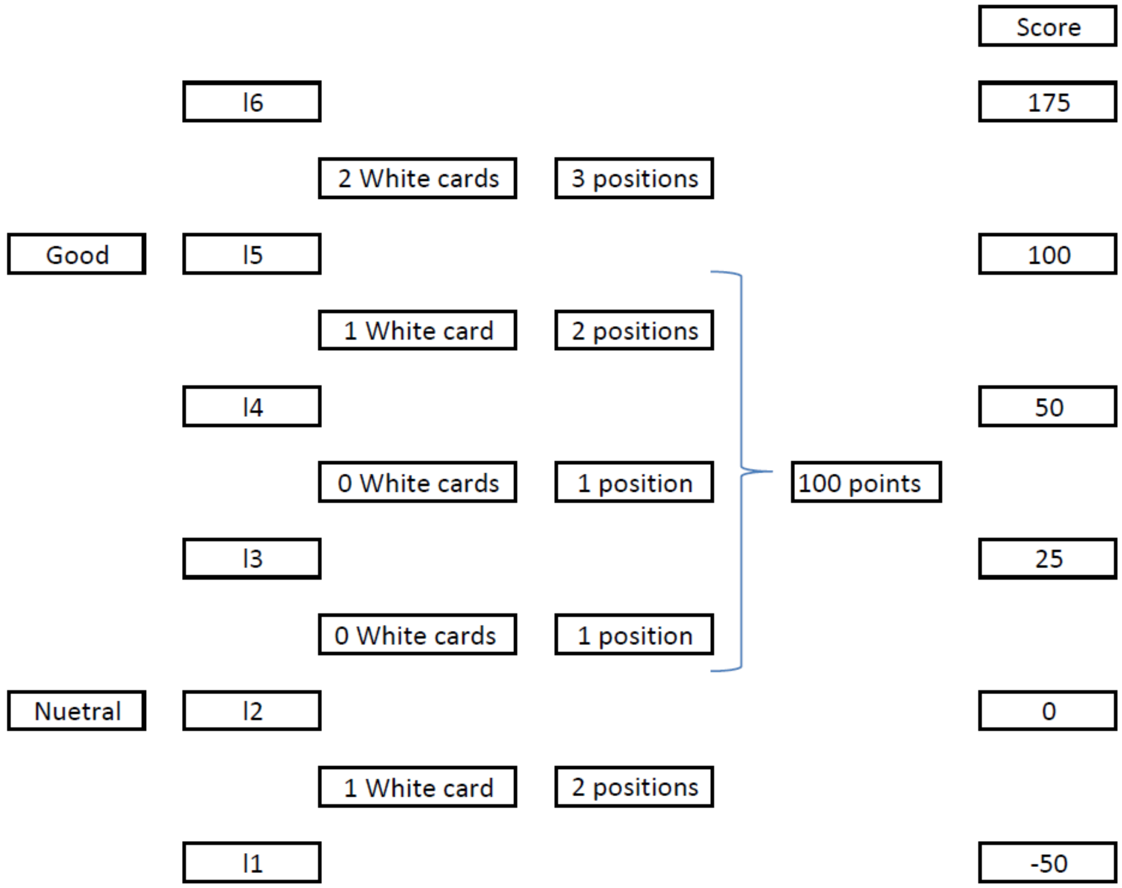


Figure 8 - Example of application of the playing cards procedure

The method, which is applied in this Master´s Dissertation to the San Francisco Bay port, may be used in future applications of the model to rank dredging equipment.

Playing cards´ model

The model is used to attribute the value of the previously ranked levels. In the procedure explained above the decision maker was asked to select one level that would be considered good and one level that would be considered neutral.

The weights assigned to these levels are zero, neutral, $k_N = 0$, and one hundred, good, $k_G = 100$.

Using a formal language:

Let

i be the position or ranking assigned,

$i = n$, for the neutral level,

$i = g$, for level good,

$i = g-1$, represents the level preceding level good,

z_i, the number of positions between level *i* and level *i+1* (this variable can assume both negative and positive integer values),

p, the value to be assigned for each position

Then:

$$p = 100 \,/ \sum_{i=n}^{g-1}(z) \tag{4}$$

One hundred points should be assigned between the level considered good and the level considered neutral; these points should be equally distributed by the positions between these two levels. The number of positions between the two values derives from the number of white cards assigned, in a proportion previously described. The denominator represents the summation of all the positions between the level considered neutral (*n*) and the level considered good (*g-1*). The value *g-1* is applied since z_{g-1} represents the number of positions between the level *g-1* and *g*.

After the value of p has been computed another formulation should be applied in order to assign weights to all levels.

$$k_i = k_{i-1} + (p \times z_{i-1}), \tag{5}$$

where: k_i is the weight of level *i*

5.2. Application of the playing cards procedure

The application of the playing cards procedure was performed in partnership with the team of decision makers from the USACE. With a list of levels already ordered, the team was asked, for each criterion, what would be the levels that the USACE would consider good and neutral. Furthermore they were asked to assign white cards to the differences between the levels, following the instructions presented on the previous section. This procedure was applied for criteria g_1, g_2, g_3, g_5, g_6, and g_7. The following paragraphs describe the procedure used and present the final points assigned to each level.

For some of the criteria, due to the high number of levels, only some cards were assigned corresponding to a part of the gaps between the levels. The team always identified the best and the worst level, the levels considered good and neutral and part of the differences in between. In order to compute the points to allocate the remaining levels the progression between them is considered linear.

For criteria 1, the USACE considers level A_OO, that represents an acceptable impact on spawning behavior and no impact on biological abundance (the species that were before occasionally present would remain occasionally present), would be considered good. While S_OO, that represents a severe impact on spawning behavior and no change on the presence of the species, would be considered neutral. Figure 9 shows the number of cards assigned to each difference and the corresponding number of positions. Grey rectangles signal the levels and the differences quantified and white rectangles signal the estimated differences. The number of points of each position is calculated using the equation below. The values assigned to the levels considered good and neutral are given.

$$p = 100 \,/ \textstyle\sum_{i=7}^{9-1}(z) = 100 \tag{6}$$

$$K_2 = k_1 + [100 \times (2)] \Leftrightarrow k_1 = -500 \quad (7)$$

$$K_3 = k_2 + [100 \times (2)] \Leftrightarrow k_2 = -300 \quad (8)$$

$$K_4 = k_3 + [100 \times (2)] \Leftrightarrow k_3 = -100 \quad (9)$$

$$K_5 = k_4 + [100 \times (1/4)] \Leftrightarrow k_4 = -75 \quad (10)$$

$$K_6 = k_5 + [100 \times (1/4)] \Leftrightarrow k_5 = -50 \quad (11)$$

$$K_7 = k_6 + [100 \times (1/4)] \Leftrightarrow k_6 = -25 \quad (12)$$

$$K_7 = 0 \quad (13)$$

$$K_8 = k_7 + [100 \times (1/2)] = 50 \quad (14)$$

$$K_9 = 100 \quad (15)$$

$$K_{10} = k_9 + [100 \times (1/2)] = 150 \quad (16)$$

$$K_{11} = k_{10} + [100 \times (1/2)] = 200 \quad (17)$$

$$K_{12} = k_{11} + [100 \times (1/2)] = 250 \quad (18)$$

$$K_{13} = k_{12} + [100 \times (1/2)] = 300 \quad (19)$$

	Levels	White cards	Positions	Points
	l_{13}			300
		1 white cards	2 positions	
	l_{12}			250
	l_{11}			200
	l_{10}			150
Good	l_9			100
		0 white cards	1 position	
	l_8			50
Neutral	l_7			0
		0 white cards	1 position	
	l_6			-25
		2 white cards	3 positions	
	l_5			-50
	l_4			-75
	l_3			-100
		0 white card	1 positions	
	l_2			-300
	l_1			-500

Figure 9- Criterion 1 (Impact on organisms), application of the "playing cards" procedure

Figure 10 shows, the function obtained from the assignment of points to all the different levels in this criterion, g_1. It is possible to observe that the initial gradient is higher than the average gradient, meaning the degradation of the environment when the environment is already weakened is worse than the same impact when the environment is healthy.

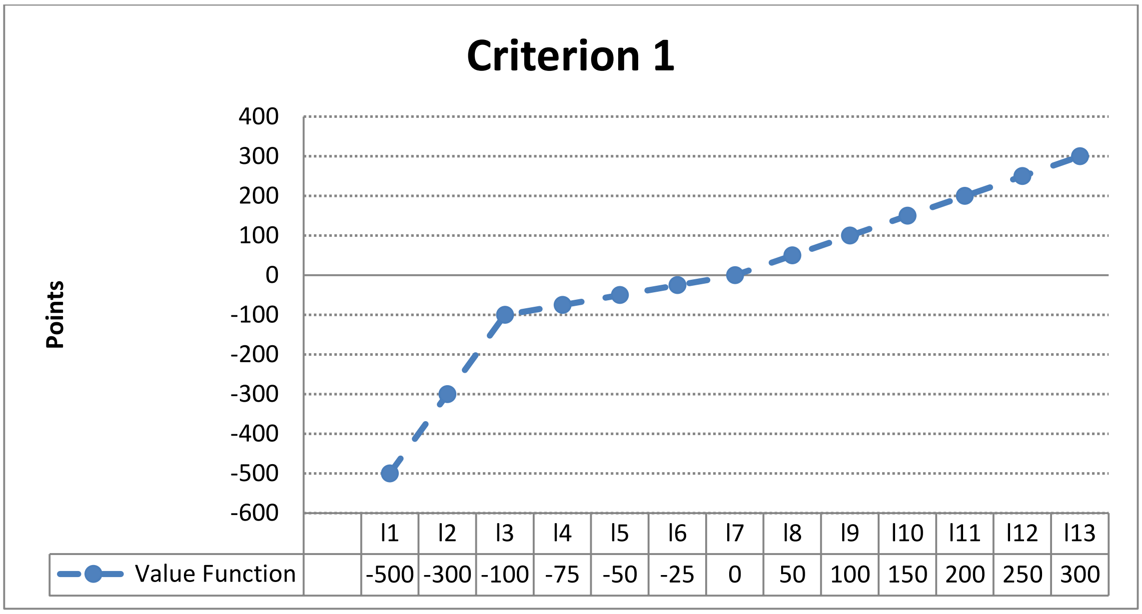


Figure 10 - Criterion 1 (Impact on organisms), function

For criteria 2, the USACE considers level AAAA (that represents acceptable values of water transparency, noise, water contamination and oxygen) good, and level AHAH (that represents acceptable values of water transparency and water contamination and high values of noise and low values of oxygen) neutral. The number of white cards and the levels that resulted from this application are presented in Figure 11.

$$p = 100 / \sum_{i=3}^{4-1}(z) = 50 \quad (20)$$

$$K_2 = k_1 + [50 \times (1)] \Leftrightarrow k_1 = -150 \quad (21)$$

$$K_3 = k_2 + [50 \times (1)] \Leftrightarrow k_2 = -100 \quad (22)$$

$$K_3 = 0 \quad (23)$$

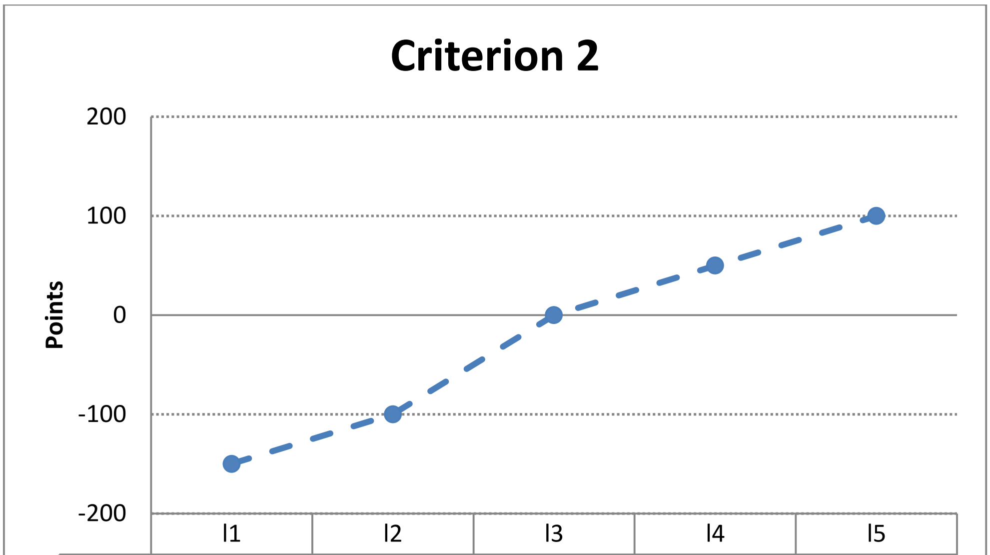
$$K_5 = k_4 + [50 \times (1)] \Leftrightarrow k_4 = 50 \quad (24)$$

$$K_5 = 100 \quad (25)$$

	Levels	White Cards	Positions	Points
Good	l_5			100
		0 white cards	1 positions	
	l_4			50
		0 white cards	1 positions	
Neutral	l_3			0
		1 white cards	2 position	
	l_2			-100
		0 white cards	1 position	
	l_1			-150

Figure 11 - Criterion 2 (Impact on spawning behavior), application of the "playing cards" procedure

Figure 12 shows the function that results from the assignment of points to the different levels in this criterion, g_2. The progression of the severity of the impact is close to linearity. However; the gradient is slightly higher in the beginning, showing that a change on the impact when the environment is already fragile leads to more severe consequences.



	I1	I2	I3	I4	I5
	-150	-100	0	50	100

Figure 12 - Criterion 2 (Impact on spawning behavior), function

For criterion 3, the USACE believes that \$15.000 would be a good price for the project and \$75.000 would be a neutral price. Furthermore, it was indicated that \$220.000 would be the maximum price charged, while \$10.000 would be the minimum price. The complete list of the levels considered is represented in Figure 13.

$$p = 100 / \sum_{i=5}^{7-1}(z) = 25 \quad (26)$$

$$K_2 = k_1 + [25 \text{ x } (1)] \Leftrightarrow k_1 = -125 \quad (27)$$

$$K_3 = k_2 + [-33] \Leftrightarrow k_2 = -100 \quad (28)$$

$$K_4 = k_3 + [-33] \Leftrightarrow k_3 = -66 \quad (29)$$

$$K_5 = k_4 + [-33] \Leftrightarrow k_4 = -33 \quad (30)$$

$$K_5 = 0 \quad (31)$$

$$K_7 = k_6 + [50 \text{ x } (1)] \Leftrightarrow k_6 = 50 \quad (32)$$

$$K_7 = 100 \quad (33)$$

$$K_8 = k_7 + [25 \text{ x } (1)] = 125 \quad (34)$$

	Levels	White cards	Positions	Points
	l_8			125
		0 white cards	1 positions	
Good	l_7			100
		3 white cards	4 positions	
	l_6			50
Neutral	l_5			0
		3 white cards	4 positions	
	l_4			-33
	l_3			-66
	l_2			-100
		0 white cards	1 position	
	l_1			-125

Figure 13 - Criterion 3 (Cost of dredging), application of the "playing cards" procedure

Figure 14 shows the scores assigned to each level in criterion 3. The price of dredging activities can assume any integer value higher than 0.

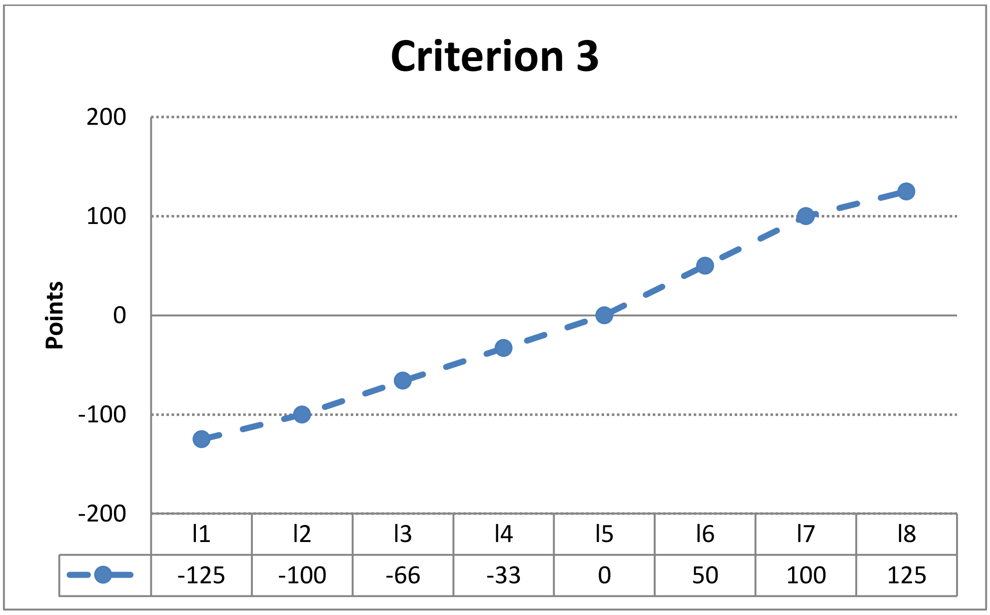


Figure 14 - Criterion 3 (Costs of dredging), function with levels

The limited budget that the USACE has to perform dredging activities is insufficient to conduct all scheduled projects. Any improvement on the expected cost of the projects would lead to the possibility of executing a higher number of dredging works. The high slope for the price values beneath $25.000 is justified by the high expectations on the number of projects that would be performed if the price was that low.

For criterion 5, g_5, the USACE considers level GA (which represents good adequacy of the machine to the physical characteristics of the sediments and acceptable adequacy of the machine to the quantity of material that needs to be dredged) good. Furthermore, it considers that a level which corresponds to a neutral performance would be AA (this level represents acceptable adequacy to both characteristics of the sediments and quantity of material that needs to be dredged). Figure 15 shows the number of white cards and corresponding number of positions between different levels.

$$p = 100 / \sum_{i=5}^{6-1}(z) = 33 \quad (35)$$

$$K_2 = k_1 + [33 \times (2)] \Leftrightarrow k_1 = -200 \quad (36)$$

$$K_3 = k_2 + [-44,3] \Leftrightarrow k_2 = -133 \quad (37)$$

$$K_4 = k_3 + [-44,3] \Leftrightarrow k_3 = -88,6 \quad (38)$$

$$K_5 = k_4 + [-44,3] \Leftrightarrow k_4 = -44,3 \quad (39)$$

$$K_5 = 0 \quad (40)$$

$$K_6 = 100 \quad (41)$$

$$K_7 = k_6 + [33 \times (2)] = 166 \quad (42)$$

$$K_8 = k_7 + [33 \times (1)] = 200 \quad (43)$$

$$K_9 = k_8 + [33 \times (1)] = 233 \quad (44)$$

	Levels	White cards	Positions	Points
	l_9			233
		1 white cards	2 positions	
	l_8			200
	l_7			166
		1 white cards	2 positions	
Good	l_6			100
		2 white cards	3 positions	
Neutral	l_5			0
		3 white cards	4 positions	
	l_4			-44,3
	l_3			-88,6
	l_2			-133
		1 white cards	2 positions	
	l_1			-200

Figure 15 - Criterion 5 (Adequacy of the equipment to the sediments), application of the "playing cards" procedure

Figure 15 shows the function that results from the assignment of points to the different levels in this criterion. The gradient is almost constant with slight increases for the lower levels and higher levels, extremes, emphasizing the importance of avoiding alternatives with very bad performance in one or both categories, quantity of sediments and characteristics of the sediments; on the other hand, it increases the incentive to select an option with very good performance in one or both categories.

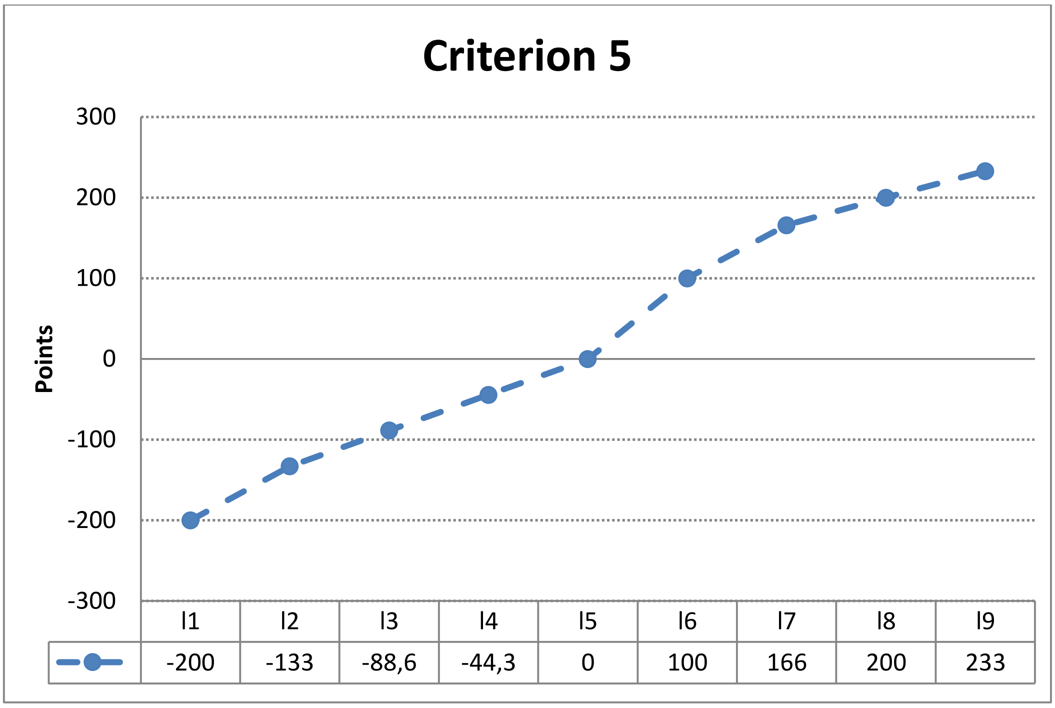


Figure 16 - Criterion 5 (Adequacy of the equipment to the sediments), function

For criteria 6, the USACE considers good level Vg (which indicates a very good adequacy of the equipment to the disposal type) and considers neutral level A (that indicates acceptable adequacy of the equipment to the disposal type). Figure 17 shows the number of cards and corresponding number of positions assigned to each level.

$$p = 100 / \sum_{i=3}^{5-1}(z) = 50 \quad (45)$$

$$K_2 = k_1 + [50 \text{ x } (1)] \Leftrightarrow k_1 = -100 \quad (46)$$

$$K_3 = k_2 + [50 \text{ x } (1)] \Leftrightarrow k_2 = -50 \quad (47)$$

$$K_3 = 0 \quad (48)$$

$$K_5 = k_4 + [50 \text{ x } (1)] \Leftrightarrow k_4 = 50 \quad (49)$$

$$K_5 = 100 \quad (50)$$

	Levels	White cards	Positions	Points
Good	l_5			100
		0 white cards	1 positions	
	l_4			50
		0 white cards	1 positions	
Neutral	l_3			0
		0 white cards	1 positions	
	l_2			-50
		0 white cards	1 position	
	l_1			-100

Figure 17 - Criterion 6 (Impact of the disposal method), application of the "playing cards" procedure

Figure 18 shows the function that result from the assignment of points to the different levels in this criterion. The function presented is linear, the USACE considers that an improvement from very bad adequacy to bad adequacy is worth the same as an improvement from bad to acceptable, acceptable to good and good to very good. This linear progression results from the consensual decision from the decision makers that there is no difference between values of improvement.

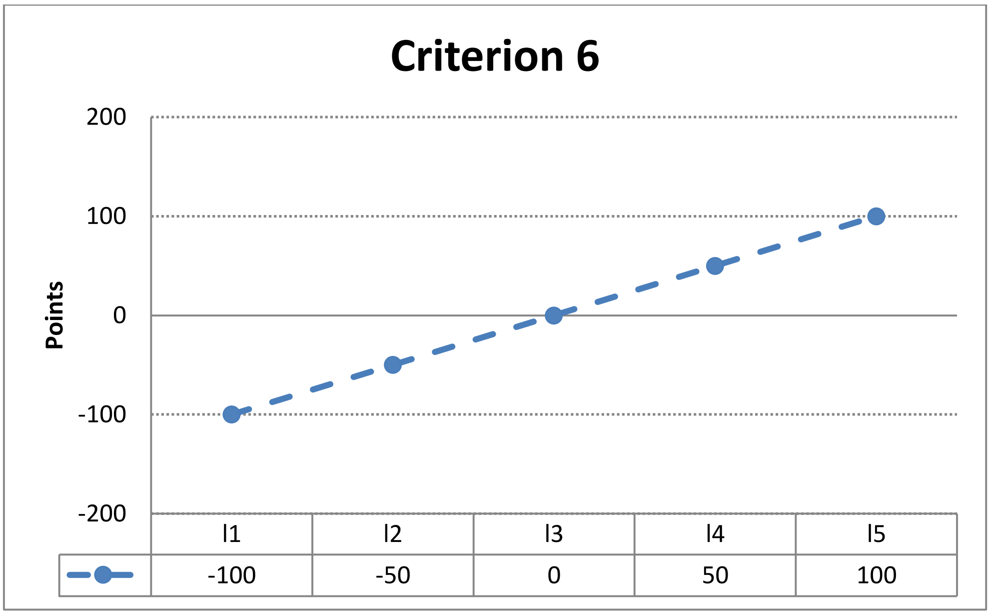


Figure 18 - Criterion 6 (Impact of the disposal method), function

For criteria 7, the USACE considers level YYGG good , this level indicates that the machine is able to perform at the given depth, is able to accomplish the required productivity, moreover the equipment has good adequacy to the distance to the disposal site and to the method of disposal. On the other hand, the USACE considers YYBB neutral, this level indicates that the machine is able to perform dredging at the given depth, is able to accomplish the required productivity, the equipment has bad adequacy to the distance to the disposal site and to the method of disposal. Figure 19 shows the number of white cards and corresponding number of positions assigned to the differences between levels.

$$p = 100 / \sum_{i=4}^{6-1}(z) = 25 \quad (51)$$

$$K_2 = k_1 + [25 \text{ x } (1)] \Leftrightarrow k_1 = -75 \quad (52)$$

$$K_3 = k_2 + [25 \text{ x } (1)] \Leftrightarrow k_2 = -50 \quad (53)$$

$$K_4 = k_3 + [-2,78] \Leftrightarrow k_3 = -25,00 \quad (54)$$

$$K_5 = k_4 + [-2,78] \Leftrightarrow k_4 = -22,22 \quad (55)$$

$$K_6 = k_5 + [-2,78] \Leftrightarrow k_5 = -19,44 \quad (56)$$

$$K_7 = k_6 + [-2,78] \Leftrightarrow k_6 = -16,67 \quad (57)$$

$$K_8 = k_7 + [-2,78] \Leftrightarrow k_7 = -13,89 \quad (58)$$

$$K_9 = k_8 + [-2,78] \Leftrightarrow k_8 = -11.11 \quad (59)$$

$$K_{10} = k_9 + [-2,78] \Leftrightarrow k_9 = -8,33 \quad (60)$$

$$K_{11} = k_{10} + [-2,78] \Leftrightarrow k_{10} = -5,56 \quad (61)$$

$$K_{12} = k_{11} + [-2,78] \Leftrightarrow k_{11} = -2,78 \quad (62)$$

$$K_{12} = 0 \quad (63)$$

$$K_{14} = k_{13} + [12.5] = \Leftrightarrow k_{13} = 12.5 \quad (64)$$

$$K_{15} = k_{14} + [37.5] = \Leftrightarrow k_{14} = 25 \quad (65)$$

$$K_{16} = k_{15} + [37,5] = \Leftrightarrow k_{15} = 62,5 \quad (66)$$

$$K_{16} = 100 \quad (67)$$

	Levels	White cards	Positions	Points
Good	l_{16}			100
	l_{15}			62,5
		2 white cards	3 positions	
	l_{14}			25
		0 white cards	1 position	
	l_{13}			12,5
Neutral	l_{12}			0
		0 white cards	1 position	
	l_{11}			-2,78
	l_{10}			-5,56
	l_9			-8,33
	l_8			-11,11
	l_7			-13,89
	l_6			-16,67
	l_5			-19,44
	l_4			-22,22
	l_3			-25
		1 white card	2 positions	
	l_2			-50
	l_1			-75

Figure 19 - Criterion 7 (Adequacy of the equipment to the physical conditions of the site), application of the "playing cards" procedure

Figure 20 shows the function that results from the assignment of points to the different levels in this criterion. The differences between most of the levels here considered are very small, indicating that minor changes in the adequacy of the equipment have almost no effect on the quality of the alternative. On the other hand, the gradients are very high for the first and for the last levels, indicating that it is very important to avoid a machine that has very bad adequacy on several categories and it greatly improves the performance to have a machine with very good adequacy.

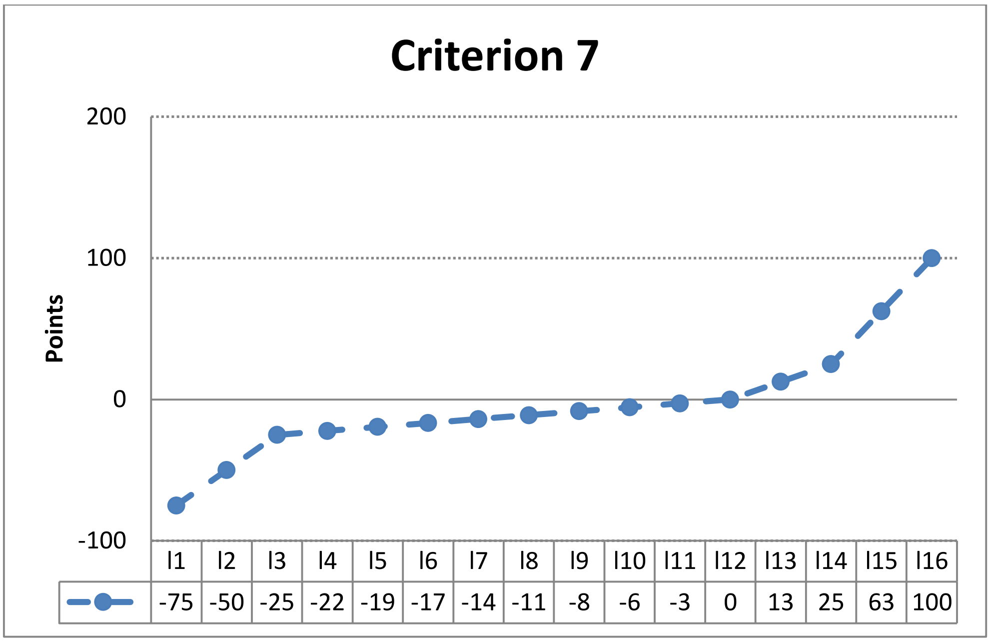


Figure 20 - Criterion 7 (Adequacy of the equipment to the physical conditions of the site), function

5.3. Defining the weights of the criteria

Once all levels have been assigned to the alternatives and the correspondent points have been computed, it is important to define the weights of each criterion in order to obtain the overall attractiveness of each machine. The assignment of weights to each criterion is performed following the swing weights procedure (Goodwin & Wright, 2009). The application of this procedure required the collaboration of the team of decision makers.

This procedure is based on the capacity of the decision makers to compare swings from the least preferred to the most preferred level on one criterion with the same swing from the least to the most preferred level in other criterion. Therefore, the decision makers are asked the following: If you could choose one criterion to change from the least preferred level to the most preferred level, what criterion would you choose? And which criterion should be chosen in the second place? These questions should be repeated until the criteria are ranked. The first criterion of the ranking should be the one that the decision maker considers as the first chosen to switch from the least to the most preferred level. On the other hand, the the last position of the ranking corresponds to the one picked last.

The ranking that results from the application of this step is:

1. Costs of dredging (g_3)
2. Impact on habitat (g_1)
3. Adequacy of the equipment to the sediments (g_5)
4. Adequacy of the equipment to the physical conditions of the site (g_7)
5. Impact of the disposal method (g_6)
6. Impact on habitat (g_2)

Once the criteria are ordered and the ranking is completed, the decision maker will help the analyst in the assessment of the differences in importance between one swing and another. To the criterion selected in the first place 100 points are assigned. The remaining points are assigned using the following steps: the decision makers are asked to compare a swing from the least to the most preferred levels in the first criterion of the ranking with the same swing in the second criteria of the ranking. This step is repeated until all swings have been compared with the swing of the first criterion of the rank. This comparison is made in terms of percentage, for example, the swing on the second criterion can be considered 80% as important as the swing in the first criterion. The original percentage weights should be normalized in the end.

The USACE considered that a swing from the worst to the best level on criterion g_1 would be 90% as important as the same swing on g_3. A swing from the worst to the best level on criterion g_5 would be 75% as important as the same swing on g_3. A swing from the worst to the best level on criterion g_7 is as important as the same swing on g_6 and these swings are 50% as important as the same swing on g_3. The last swing compared was g_2, this swing is considered 30% as important as the same swing on g_3. The relative importance of the swing is represented on Figure 21.

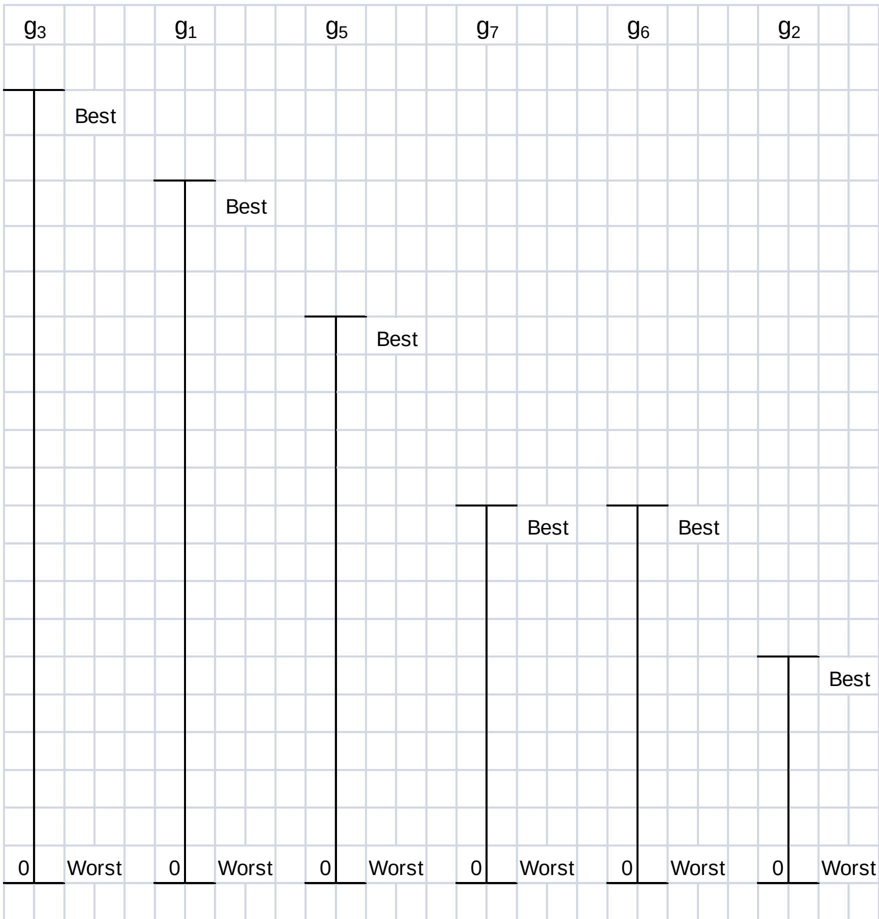


Figure 21 - Derivation of swing weights

The normalization, to sum 100, of the values obtained in the application of the swing weights procedure resulted in the weights of the criteria, represented in Table 19.

Table 19 - Non normalized and normalized weights of the criteria

Non normalized weights		Normalized weights	
k_3	100	w_3	25,5
k_1	90	w_1	23
k_5	75	w_5	19
k_7	50	w_7	12,5
k_6	50	w_6	12,5
k_2	30	w_2	7,5
Sum	395	Sum	100

For the San Francisco Bay port, each criterion was constructed using dimensions, which implied verifying if the assessment made considering only the criteria matches the assessment made considering the dimensions. For this reason, the decision maker should also be asked what weight to assign if dimensions are considered instead of criteria. Any inconsistencies found should be reviewed and the causes cleared out. This confirmation was done with the support of a group of experts from USACE and no inconsistencies were found.

5.4 Assignment of levels to the available equipment

The assignment of levels to each machine, according to its characteristics, was performed with help of the team of decision makers from the USACE. It was with their support that some changes in the criteria and corresponding levels were introduced and the final form of the criteria tree was reached.

The first step of this collaboration was the precise definition of the environment in which the dredging activities were to take place. The San Francisco Bay port has a wide area and the conditions are not homogeneous throughout the entire region. It was estimated that a total of 10,000 cubic yards of sandy material needed to be dredged; the disposal would be processed using open water placement at the San Francisco Channel Bar, 3 nautical miles away from the mouth of the Bay. It was also settled that the project would respect the EWs defined by EPA (United States Environmental Protection Agency). Since it is a new dredging project, not a maintenance project, sediments are more densely packed than usual and vegetation holds it together better.

This evaluation was repeated for a set of five types of dredges: cutter-suction, dustpan, water injection, clamshell and dipper. There are other types of dredges available, but they were excluded from this analysis as they were considered very uncommon or dominated by the ones presented.

The following section presents the assigned levels and a brief justification for each.

5.4.1. Assignment of performance levels to each alternative

For dimension 1(Biological abundance), the first step was the selection of the best suitable initial scenario: it was considered that before dredging activities took place, species were occasionally present in the site. This scenario is maintained after dredging when clamshell, dipper, dustpan or injection water dredges are used and changes in to rarely present when cutter-suction is used. It was assumed that cutter-suction dredges are slightly more likely to remove organisms from the site.

For the second dimension (Impact on the spawning behavior) the impact on the reproductive behavior was studied. Even considering that dredge activities take place respecting the EPA´s EW, the impact is not negligible. The impact of clamshell, dipper, cutter-suction and dustpan dredges is severe, while the use of water injection dredges is more likely to affect reproductive behavior. The level assigned to this equipment was V, very severe impact.

For dimension 3 (Turbidity), the first dimension of criterion 2, it was considered that the machines whose performance involves the agitation of large amounts of sediments cause higher levels of turbidity and therefore low values of water transparency. To these machines, cutter-suction, dustpan and water injection, the level assigned was Lv, low values of water transparency. On the other hand, for the two mechanical dredges, clamshell and dipper, whose activity is responsible for less agitation, level Av, acceptable values of water transparency, was assigned.

For dimension 4 (Noise), the machines were once again divided in two groups. The first group, which included non-mechanical machines (cutter-suction, dustpan and water injection) works producing a lot of water agitation and is also associated with of high levels of noise, so level Hn (high values of noise) was assigned. The two mechanical equipment (clamshell and dipper dredges) produce less agitation and therefore less noise, level An, acceptable levels of noise, was assigned.

For dimension 5 (Contamination), it was considered that the contamination caused by the equipment itself is not significantly different from one machine to the other. However, methods that result on a high agitation of water are responsible for larger contamination scenarios when the sediments that are being dredged are contaminated. In this sense, level Hc, high levels of contamination, was assigned to cutter-suction, dustpan and water injection dredges, while level Ac, acceptable levels of contamination, was assigned to clamshell and dipper dredges.

The results of dimension 6 (Oxygen reduction) were also influenced by the agitation of the water. This agitation results in the decrease of the amount of light that reaches photosynthetic organisms which produce oxygen, and hence decreases the level of dissolved oxygen. This results on the assignment of Lo, low values of oxygen, to cutter-suction, dustpan, and water injection dredges, and Ao, acceptable values of oxygen, to clamshell and dipper dredges.

For the third criterion (Costs of dredging), the discriminated data for each dimension was not available. Therefore only the value of the total dredging costs was considered. The dredging equipment considered can be divided into three categories: bucket, hopper and pipelines. The information on the costs is available by category of equipment. In the first category, bucket dredges, clamshell and dipper dredges are included and the estimated costs are $11.30 per cubic yard. It was assumed that in the dredging scenario considered 1000 cubic yards needed to be dredged, with an estimated cost of approximately $113.000. In the second category, pipeline dredges, water injection dredges are included the estimated cost is $8.80 per cubic yard, which results on $88.000 total costs for this project. The last category is the set of hopper dredges. That include cutter-suction and dustpan dredges, the estimated cost is $2.5 per cubic yard, $25.000 for this project.

The fourth criterion (Utility or externalities), although very important, was not considered in this analysis. There are several reasons to justify this elimination. The fact that for this evaluation equal dredging and disposal locations were considered leads to equal end results, which means equal benefits. Secondly, since it is considered that the project has a goal, for example, construct a new water navigable channel, then the externality caused by the existence of this new channel is also the same whichever the machine selected. Furthermore, the estimation of these values is not usually performed. The need to perform dredging is easily identified, although the overall benefits of the projects are not usually quantified. It could, however, be interesting in order projects.

For the fifth criterion (Adequacy of the equipment to the sediments), it was considered that the primary material in San Francisco Bay is sand, although more densely packed than usual since this is a new dredging site. Clamshell dredges cannot adequately grab sand, they can, however, grab more densely packed materials. As for dealing with large amounts of sediments, these are not the most adequate dredges. Therefore, the level assigned was AA, acceptable adequacy, to the sediments and to the amount of material that needs to be dredged. Dipper dredges can easily deal with the type of sediments considered but are limited in size. For these reasons, level VgB was assigned, meaning that the equipment has very good adequacy to the type of sediments but bad adequacy to the amount that needs to be dredged. Cutter-suction dredges are perfectly adequate for sandy sediments but not for more densely packed sediments. These machines have limitations concerning their quantity capacity, level GA was assigned, meaning the equipment has good adequacy to the type of sediments and acceptable adequacy to the amounts of sediments that needs to be dredged. Dustpan dredges can easily deal with sand but not so with other types of sediments or to move any type of sediments, for these reasons the level assigned was BB, which means bad adequacy for both types of sediments and amount of sediments. Water injection dredges can easily deal with large amounts of sediments but have problems with sediments that are not sand. Level BVg was assigned, meaning that the equipment has bad adequacy for the type of sediment but very good adequacy for the type of sediments.

The sixth criterion (Impact of the disposal method) is associated with the adequacy of the equipment to the disposal type, in this scenario, open water disposal at San Francisco Bay. It was considered that clamshell, dipper and dustpan dredges have a very good adequacy to the disposal type. Cutter-suction dredges have an acceptable adequacy, while water injection dredges would have a poor performance, they have very bad adequacy to disposal in open waters.

For the seventh criteria (Adequacy of the equipment to the physical conditions of the site), four levels were assigned, one and for each dimension for each machine. The first dimension, dimension 15 (Dredging depth), indicates if a machine is capable or not of performing dredging activities at the given depth. The same equipment can deal with different depth capacities. For this analysis the average size was considered. Thus, in general, cutter-suction, dustpan, water injection and clamshell dredges are capable of dredging in this scenario, while dipper dredges is not.

Dimension 16 (distance to the disposal area) indicates the adequacy of the machine to the distance between the dredging and the disposal sites. Cutter-suction and dustpan dredges have some transportation capacity and their adequacy is considered acceptable. Water injection dredges can only be used in areas where natural currents flows take care of the disposal. If the dredging and disposal sites are separated these machines are not adequate, they have bad adequacy. The clamshell and dipper dredges usually load the sediments into a scow or other transport boat which allows them to easily dispose the material on the most convenient place. Their adequacy is considered good.

Dimension 17 (Physical environment) is related with the capacity of the equipment to deal with adverse water conditions. In the San Francisco Bay the currents are not strong however some machines are more adequate than others. Cutter-suction dredges are usually sturdy enough to handle some turbulence, it is considered that they have acceptable adequacy. Clamshell and dipper dredges can also work in moving waters, they are considered to have acceptable adequacy. On the other hand, dustpan dredges can only work with still water, it is considered that they have bad adequacy, just as water injection dredges that can only work in areas with specific moving water.

Dimension 18 (Production required) relates with the capacity of the dredges to deal with the productivity required. Although cutter-suction, dustpan and injection water dredges are more productive, clamshell and dipper dredges can also meet the production requirements for dredging in the San Francisco Bay.

The summarized performance of the machines is presented on the Table 20.

Table 20 – Performance´s levels assigned to each machine

Machines	g_1	g_2	g_3	g_4	g_5	g_6	g_7
Cutter-suction	S_OR	LHHL	$25.000	n.a	GA	A	YYAA
Dustpan	S_OO	LHHL	$25.000	n.a	BB	Vg	YYAB
Water injection	V_OO	LHHL	$88.000	n.a	BVg	Vb	YYBB
Clamshell	S_OO	AAAA	$113.000	n.a	AA	Vg	YYGA
Dipper	S_OO	AAAA	$113.000	n.a	VgB	Vg	NYGA

The overall performance of the dredging equipment is computed. Table 21 presents the points assigned to each machine in each criterion according to their performance.

Table 21 – Values of each machine

Machines	g_1	g_2	g_3	g_4	g_5	g_6	g_7
Cutter-suction	-100	-150	50	n.a	100	0	25
Dustpan	0	-150	50	n.a	-88,6	100	12,5
Water injection	-50	-150	-33	n.a	100	-100	0
Clamshell	0	100	-66	n.a	0	100	62,5
Dipper	0	100	-66	n.a	100	100	-8,33

The performance of each machine in each criterion are aggregated using an additive model. This model consists on the simple addition of the points given to each alternative in each criterion using the weights of each criterion, presented on the previous section of this chapter. Table 22 aggregates the weighted performance of the alternatives.

Table 22 - Overall performance of the equipment, additive model

Machines	w_1xk_1	w_2xk_2	w_3xk_3	w_4xk_4	w_5xk_5	w_6xk_6	w_7xk_7	Score
Cutter-suction	23	-11,25	12,75	n.a	19	0	3,125	46,63
Dustpan	0	-11,25	12,75	n.a	-16,834	12,5	1,5625	-1,27
Water injection	11,5	-11,25	-8,415	n.a	19	-12,5	0	-1,67
Clamshell	0	7,5	-16,83	n.a	0	12,5	7,8125	10,98
Dipper	0	7,5	-16,83	n.a	19	12,5	-1,04125	21,13

The number that results from the application of the additive model is the result off the overall performance of the alternative. Better performances are associated with higher values, while low values correspond to worse performances. Table 23 presents the ranking and the overall score of each machine.

Table 23 - Ranking of the alternatives

Ranking	Machine	Score
1st	Cutter-suction	46,63
2nd	Dipper	21,13
3rd	Clamshell	10,98
4th	Dustpan	-1,27
5th	Water injection	-1,67

5.5. Sensitivity Analysis

The sensitivity analysis is conducted in order to check the robustness of the results. For this problem, it is important to test if the ranking initially obtained remains unaltered, with variations on the weights assigned to each criterion. It was considered that the "error" on the assignment of the points does not exceed 10%. Therefore, for each criterion, it was tested an increase and a decrease of 10% of the points assigned by the decision maker. In order to further test the results, the needed weight´s value for the ranking to be altered were calculated. Each criterion is tested separately and the remaining weights should be recalculated granting that the relative importance previously established is maintained. A final aggregated test was also performed, the criteria would be divided into groups; this division is useful to test changes in a set of criteria, in this case, negative externalities and benefits would constituted the two groups.

These sensitivity analysis follows the techniques learned in Decision Analysis classes and the guidelines proposed and exemplified in the literature (Goodwin & Wright, 2009).

The analyses were ordered in descending order of weight of the criteria. The first analysis was performed was in g_3, followed by g_1, g_5, g_7, g_6 and g_2.

The first analysis tested what would happen if the points assigned to criterion k_3 were to suffer a 10% decrease. For this case the increase of 10% was not tested since the criterion already received 100 points. The analysis was performed considering that the weight structure for the remaining criteria would be maintained. The results obtained are presented in Table 24.

Table 24 – Criteria´s weights, decrease of 10% on criterion 3

Normalized weights	
w_3	23,38
w_1	23,38
w_5	19,48
w_7	12,99
w_6	12,99
w_2	7,79
Sum	100

The new weights should be applied in order to obtain the new raking of the machines. Table 25 shows the new scores and ranking. It is possible to observe that if the points assigned to criterion 3 decreased by 10% no changes would be verified.

Furthermore, Figure 22. shows that the ranking would not change no matter how much the weight assigned to k_3 is changed.

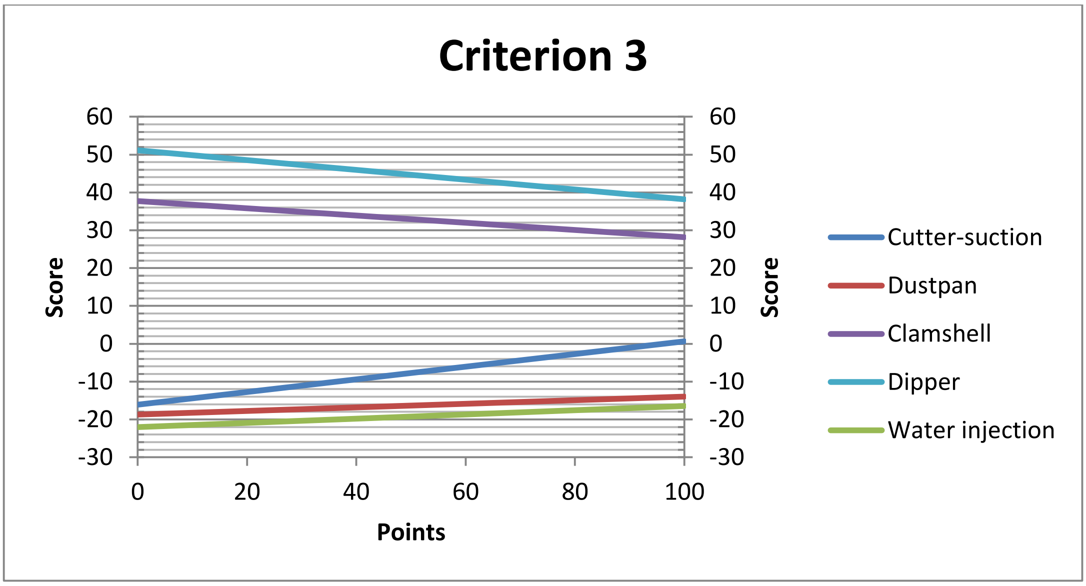


Figure 22 - Sensitivity analysis, criterion 3

Dipper and the clamshell dredges are very penalized by the high weight assigned to criterion 3, the estimated cost of dredging with a clamshell or a dipper dredges is more than 4 times higher than the cost of dredging with a cutter-suction dredge.

Table 25 shows the new scores and ranking considering a decrease of 10% on the weight assigned to g_3.

Table 25 – Final scores and ranking considering a decrease of 10% on the weight assigned to *k_3*

Ranking	Machines	g1	g2	g3	g4	g5	g6	g7	Score
3rd	**Cutter-suction**	-23,38	-11,69	11,69	n.a	19,48	0,00	3,25	-0,65
4th	**Dustpan**	0,00	-11,69	0,00	n.a	-17,26	12,99	1,62	-14,33
5th	**Water injection**	-11,69	-11,69	0,00	n.a	19,48	-12,99	0,00	-16,89
2nd	**Clamshell**	0,00	7,79	0,00	n.a	0,00	12,99	8,12	28,90
1st	**Dipper**	0,00	7,79	0,00	n.a	19,48	12,99	-1,08	39,18

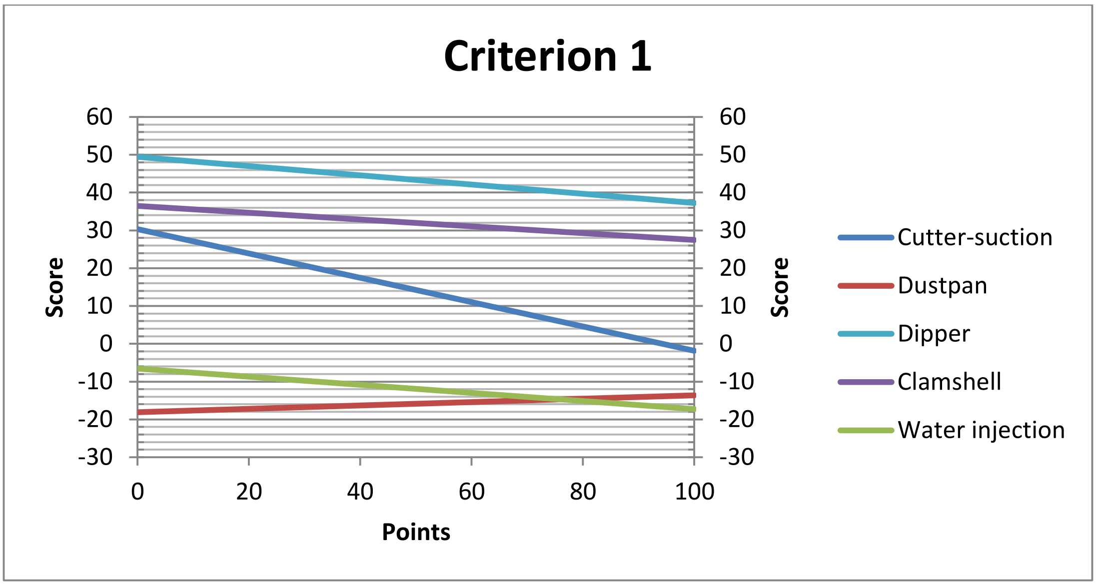
The second analysis tested what would happen if the points assigned to criterion 1 would increase by 10% or decrease by 10%. The analysis was performed considering that the weight structure for the remaining criteria would be maintained. Table 26 shows on the left the normalized weights that result from an increase of 10% on the points assigned to criterion 1, g_1, while on the right it is shown the normalized weights if the points assigned to criterion 1 decrease by 10%.

Table 26 - Criteria´s weights, increase and decrease of 10% on criterion 1

Normalized weights		Normalized weights	
w_3	24,75	w_3	25,91
w_1	24,50	w_1	20,98
w_5	18,56	w_5	19,43
w_7	12,38	w_7	12,95
w_6	12,38	w_6	12,95
w_2	7,43	w_2	7,77
Sum	100	Sum	100

Figure 23 illustrates what happens when the weight of criterion 1 is changed. If only a decrease and an increase of 10% of the points assigned are considered, then there is no change in the ranking. Even if higher variations are considered, there is no change in the ranking of the top three alternatives. On the other hand, if the points assigned to criterion 1 are below 80, the dustpan alternative presents a better overall score than the water injection dredger.

Figure 23 - Sensitivity analysis, criterion 1



The third analysis tested what would happen if the points assigned to criterion 5 were increased or decreased by 10%, considering that the weight structure for the remaining criteria is maintained. Table 27 (left) shows the normalized weights that result from an increase of 10% in the points assigned to criterion 5 and the normalized weights if the points assigned to criterion 1 decrease by 10% (right).

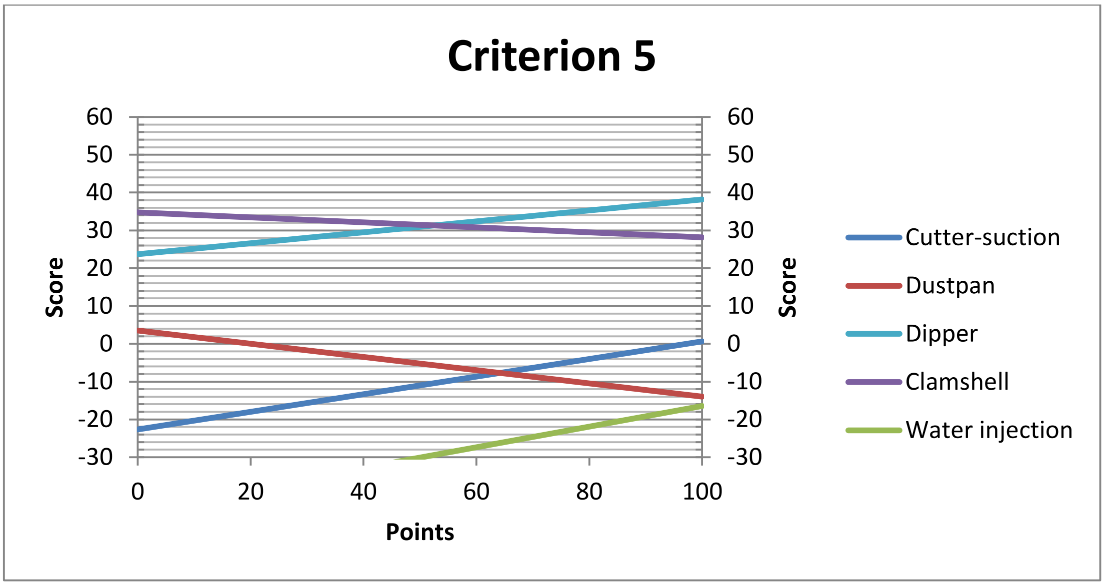
Table 27 - Criteria´s weights, increase and decrease of 10% on criterion 5

Normalized weights		Normalized weights	
w_3	24,84	w_3	25,81
w_1	22,36	w_1	23,23
w_5	20,50	w_5	17,42
w_7	12,42	w_7	12,90
w_6	12,42	w_6	12,90
w_2	7,45	w_2	7,74
Sum	100	Sum	100

Figure 24 describes what happens when the weight of criterion 5 is changed. If only a decrease and an increase of 10% in the points assigned are considered, then there is no change in the ranking. With an increase of 10% in the points assigned, the only change observed is a switch between the fourth and the fifth position of the ranking. If points assigned decrease by 10% no changes are found.

In order to change the ranking of the two alternatives with the best overall score it is necessary that the points assigned to criterion 5 are equal or below 35. In this scenario, the clamshell dredger presents a better overall score than the dipper dredger. This scenario would imply a decrease of 64% of the points initially assigned to this criterion.

Figure 24 - Sensitivity analysis, criterion 5



The capability of the machines to deal with the type of sediment and the quantity of sediments is very important and the weight assigned to this criterion would never be low enough to change the results initially obtained.

The forth analysis tested what would happen if the points assigned to criterion 7 were increased or decreased by 10%, considering that the weight structure for the remaining criteria would be maintained. The new weights are presented in Table 28.

Table 28 - Criteria´s weights, increase and decrease of 10% on criterion 7

Normalized weights		Normalized weights	
w_3	25,00	w_3	25,64
w_1	22,50	w_1	23,08
w_5	18,75	w_5	19,23
w_7	13,75	w_7	11,54
w_6	12,50	w_6	12,82
w_2	7,50	w_2	7,69
Sum	100	Sum	100

Figure 25 describes what happens when the weight of criterion 7 is changed. If only a decrease and an increase of 10% in the points assigned are considered, there is no change on the ranking. The score of the two best alternatives gets closer when the number of points assigned to criterion 7 increases, however, even when 100 points are assigned, dipper dredges still perform better then clamshell dredges.

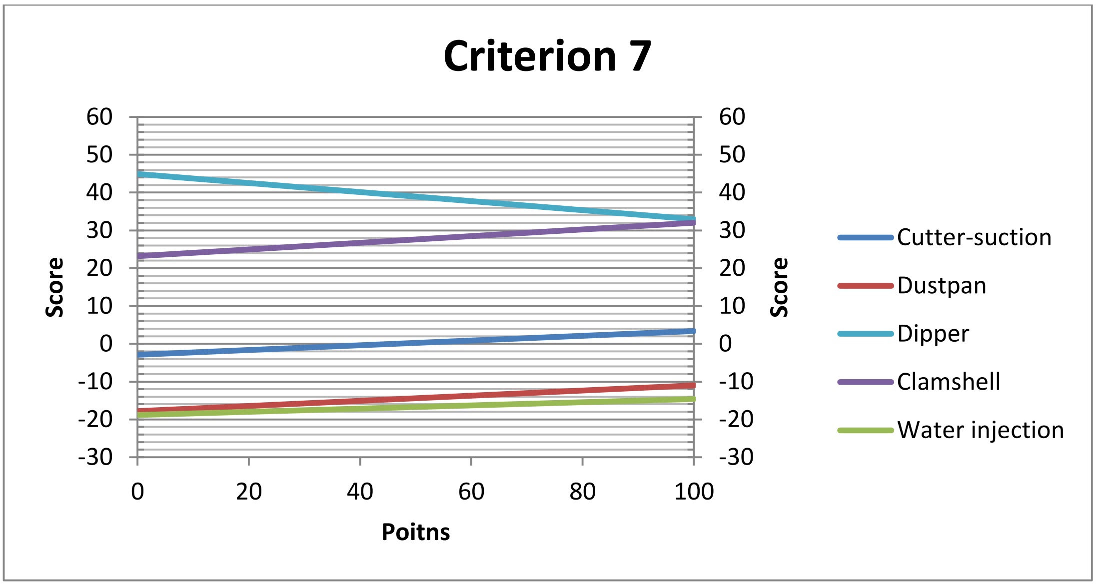


Figure 25 - Sensitivity analysis, criterion 7

The fifth analysis tested what would happen if the points assigned to criterion 7 were increased or decreased by 10%, considering that the weight structure for the remaining criteria would be maintained, as shown in Table 29.

Table 29 - Criteria´s weights, increase and decrease of 10% on criterion 6

Normalized weights		Normalized weights	
w_3	25,00	w_3	25,64
w_1	22,50	w_1	23,08
w_5	18,75	w_5	19,23
w_7	12,50	w_7	12,82
w_6	13,75	w_6	11,54
w_2	7,50	w_2	7,69
Sum	100	Sum	100

Figure 26 describes what would happen when the weight of criterion 6 is changed. If only a decrease and an increase of 10% on the points assigned are considered then there is no change on the ranking. The increase of 10% produces no changes in the ranking, on the other hand, a decrease of 10% on the points assigned to criterion 6 results in a switch between the fourth and the fifth positions.

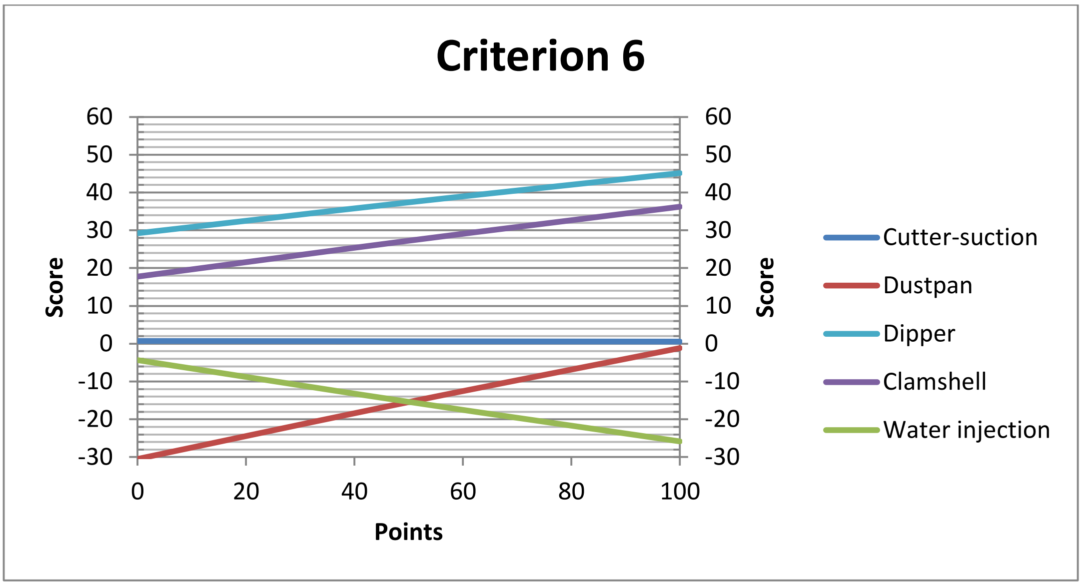


Figure 26 - Sensitivity analysis, criterion 6

The sixth analysis tested what would happen if the points assigned to criterion 7 would be increased or decreased by 10%, considering that the weight structure for the remaining criteria would be maintained, as it is presented in Table 30.

Table 30 - Criteria´s weights, increase and decrease of 10% on criterion 2

Normalized weights		Normalized weights	
w_3	25,13	w_3	25,51
w_1	22,61	w_1	22,96
w_5	18,84	w_5	19,13
w_7	12,56	w_7	12,76
w_6	12,56	w_6	12,76
w_2	8,29	w_2	6,89
Sum	100	Sum	100

Figure 27 describes what happens when the weight of criterion 2 is changed. If only a decrease and an increase of 10% on the points assigned are considered then there is no change in the ranking.

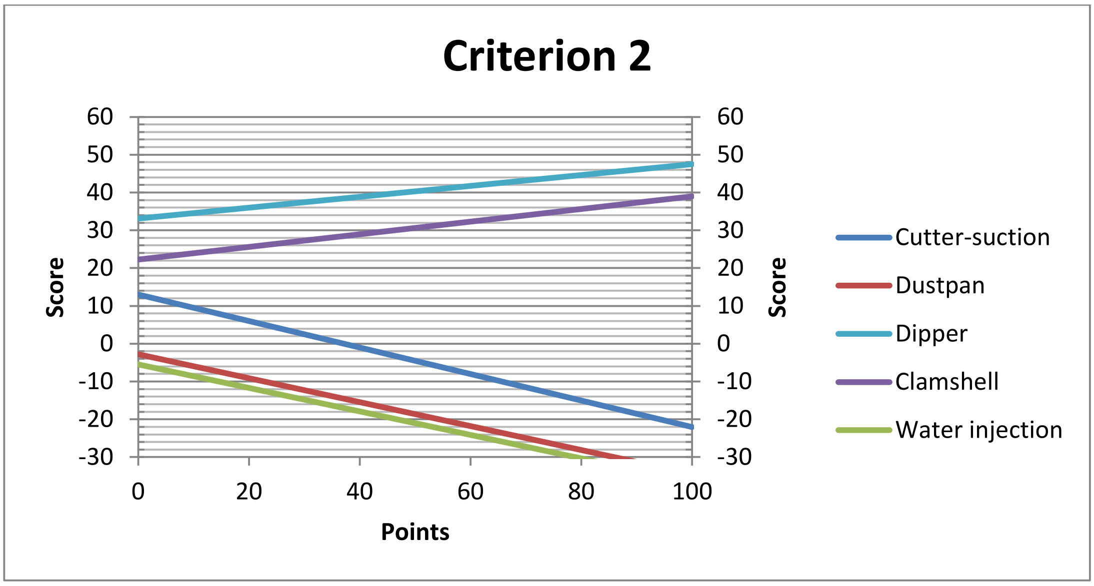


Figure 27 - Sensitivity analysis, criterion 2

It is interesting to also test a scenario in which only the technical criteria affect the decision. In this case all other non-technical criteria are eliminated, impact on organisms (g_1), impact on habitat (g_2) and cost of dredging (g_4). The seventh analysis presents a scenario where only the adequacy of the equipment to the sediments (g_5), impact of the disposal method (g_6) and adequacy of the equipment to the physical conditions of the site (g_7), are relevant, considering that the weight structure for the remaining criteria would be maintained. The weights are therefore normalized excluding criteria, g_1, g_2 and g_3, as shown in Table 31.

Table 31 - Criteria´s normalized weights excluding criterion 1,2 and 3

Normalized weights	
w_3	0,00
w_1	0,00
w_5	42,86
w_7	28,57
w_6	28,57
w_2	0,00
Sum	100

The cutter-suction leaves the first place overtopped by the dipper dredges, the two alternatives switch places. Nevertheless, it is important to notice that even if only the technical criteria are considered, the ranking of the alternatives does not change drastically. The first position switches with the second place and the fourth switches with the fifth. Table 32 presents the new score and ranking.

Table 32 - Final scores and ranking excluding criterion 1,2 and 3

Ranking	Machines	g1	g2	g3	g4	g5	g6	g7	Score
2nd	**Cutter-suction**	0,00	0,00	0,00	n.a	42,86	0,00	7,14	50,00
5th	**Dustpan**	0,00	0,00	0,00	n.a	-37,97	28,57	3,57	-5,83
4th	**Water injection**	0,00	0,00	0,00	n.a	42,86	-28,57	0,00	14,29
3rd	**Clamshell**	0,00	0,00	0,00	n.a	0,00	28,57	17,86	46,43
1st	**Dipper**	0,00	0,00	0,00	n.a	42,86	28,57	-2,38	69,05

5.6. Interaction with the decision makers

The construction and application of the model developed in this Master´s Dissertation was only possible with the collaboration of the USACE experts, here acting as decision makers. Their support was essential for the development and selection of the FPV, criteria and dimensions, clarification of the performance of each alternative and definition of the criteria´s weights. Although some of the interactions were already described, this section will present them in more detail. The communication was performed using both telephone and email. The interaction with the USACE can be divided in several steps.

The first step was the collection of data about the USACE and its activities. In this stage I contacted my co-advisor Igor Linkov and Engineer Mathew Bates both by email and telephone.

The second step was the development of the criteria tree, initially the tree was developed using, documents from the USACE that had broad lines about the procedures and the criteria that were used to select dredging machines in the past. The selected criteria, dimensions and scales were integrated on a criteria tree that was presented to the USACE. Throughout this process, several improvements were presented, studied and implemented, until the tree reached its final form, ultimately validated by the USACE. The team of decision makers which included Engineer Mathew Bates, Engineer Cate Fox-Lent and Engineer Zachary Collier was formed. All answers given were the result of discussion and consensus of the team.

The third step included the ranking of the different levels, the quantification of the performance differences between the levels and the definition of the weights of each criterion. Here the interaction was performed by email with the decision makers. Some of the information required in this phase involved teaching the decision makers to apply some procedures, namely the “playing cards” procedure. The instructions were briefly presented, side by side with explanations and examples. No difficulties were found in this step, which indicates that the methodology is simple enough to be reapplied to other sites with no extra support.

The fourth step was the final validation of the overall model and results. Here, once again, it was crucial the support of the decision makers to clarify all doubts and present justifications for all the assignments. This step was important, for example, to clarify the reason why some of the alternatives have a negative score and the remaining have low positive scores. This is due to the fact that criterion g_4 was not accounted. This was the criterion that measures the positive impact, externalities of the dredging projects turning the negative scores into positive. The exclusion of criterion 4 was justified by the decision makers: since these alternatives were meant for the same place, purpose and final results, the expected positive externalities were also the same. For other scenarios, in which the expected results are not as well defined as in this case study, the inclusion of g_4 would be essential. The inclusion of this criterion would cause a parallel shift of the results. It was also in this moment that the validation of the weights assigned to the criteria were validated, confirming that if the weights would have been assigned to the dimension instead of to the criteria the same results would have been obtained.

The fifth step was the performance of the sensitivity analysis, were the robustness of the results obtained was checked.

5.7. Interpretation of results

The application of this model to the San Francisco Bay port intended to test the model and verify the quality of the ranking produced.

Depending on the characteristics of the site and the sediments that need to be dredged, the machines can be more or less adequate. Considering the environmental, economic and technical data, the model is able to weight and score each machine according to its capacity to accomplish the required dredging.

For the specific conditions of the San Francisco Bay port, the model shows that the cutter-suction dredges are, the best alternative as they present an overall better performance. The score computed for this machine is twice as much the score obtained by the dipper dredges, the second in the computed ranking. The successful performance of the cutter-suction is based on its excellent technical performance, controlled impact on habitat and acceptable price. This alternative does not, however, dominate, the others in all criteria. Its weaknesses are the impact on environment and the impact of disposal. The cutter-suction does not present the best technical performance nor the cheapest price, but it shows the overall best performance.

Two of the machines considered have very low overall scores, negative points, indeed. These alternatives are the dustpan and the water injection dredges; they are not adequate for the scenario considered. Their characteristics could be useful in different scenarios, tough.

The dipper dredges are the best technical alternative for the site and have little environmental impact on habitat and on environment. This alternative is dominated by cutter-suction dredges due to price restrictions. The price for square fit of dredging with dipper dredges is almost five times the price of dredging using a cutter-suction dredge.

The clamshell has an acceptable overall score, its advantages are the technical adequacy and little impact on habitat and environment. This is also an expensive alternative that has significant disposal impacts.

The model helped weighting the criteria and reaching the overall score of each equipment. If the model is applied to other sites, where different conditions are considered or if it is applied to another set of machines, a new ranking would be built.

For the San Francisco Bay port, the USACE should use a cutter-suction dredger, the machine that presented the best overall performance.

5.8. Conclusions

This chapter purpose was to develop a standard model that could be applied to other sites and to any given set of machines and produce a ranking of the studied alternatives to the San Francisco Bay port.

The first phase was the development of the model, based on all the generic information related to dredging and the most relevant concerns when selecting dredging machines. Once all the levels were created, an adaptation of the revised J. Simos procedure by José Figueira and Roy with modification by J. Figueira (2014) was applied, allowing the differences between levels to be quantified. This application ignored the levels that were assigned to the set of machines of the San Francisco Bay port, this abstraction resulted on a complete quantification of the difference between all levels that is essential for the application of the model to other scenarios.

The Swing weights technique, selected due to its simplicity, was used to assign weights to the criteria; the technique was easily understood by the USACE, which can decide, in the future, to change the relative importance of each criterion.

The application of the model required detailed information about the site, the dredging works and the set of machines available. The model is able to assign scores, using the information collected with the USACE, to each machine according to its adequacy and capacity to perform dredging activities for the given dredging project. For the San Francisco Bay port case, it was able to signalize the best alternatives and a couple of acceptable and inadequate options, helping the decision makers in the selection of the equipment. It successfully ranked the alternatives.

The ranking obtained was tested, using a sensitivity analysis, and its robustness was proven, validating not only the results for the San Francisco Bay port, but also proving the viability of the application of the model to new scenarios.

6. Final conclusions and future research

This Master Dissertation formulates a methodology to rank and select dredging equipment, and applies it to the specific example of the San Francisco Bay.

The Dissertation starts with the definition of the context of dredging activities and a review of methodologies currently used.

Based in the information and publications of the USACE (United States Corp of Engineering), this work considered machines and sites where dredging takes place. It then addressed the determination of the conditions and criteria currently used to select the most adequate equipment.

The literature review presented refers several relevant papers on previously developed work with application of MCDA (Multi-Criteria Decision Analysis) to problems related to dredging, environment or water ports, and harbor management. It also includes information collected in papers where alternative methodologies to MCDA were applied to similar problems. The review concludes that a wide diversity of methodologies and approaches are used. The Master´s Dissertation intends to take advantage of the benefits of each approach and to reduce the impact of their limitations by using an MCDA *integrated approach*. This was considered the most suitable methodology. This review is instrumental to the development of the model.

The model proposed tries to include and organize as much information as possible. It incorporates FPVs (Fundamental Point of View) criteria, dimensions, elementary consequences and primary or ordinary scales. Due to the diversity of criteria developed several construction techniques were used.

Once all dimension´s levels were defined and the criteria's levels were identified the application phase could take place.

The application phase starts with the definition of the decision maker´s preferences in what regards the levels defined for each criterion. The decision maker expressed how much better each level was compared with the previous level. The definition was conducted using the playing cards procedure, a technique in which the decision maker is given a set of cards and attributes cards to the differences between two consecutive levels. The number of cards assigned is crucial in the definition of the score of each level.

The assignment of the weights to each criterion is also mandatory; these weights are used to calculate the overall score of each alternative. Here, a swing weight´s procedure was applied.

For validation purposes, the model developed was applied to a dredging site in the San Francisco Bay port. The information about the site was collected by the USACE and introduced in the model producing a rank of the machines available. The results obtained were validated and presented to the USACE.

To simultaneously test how robust the model and the selected alternative are to changes in the weights of the criteria, a sensitivity analysis was performed. This analysis allows also the estimation of the changes in the weights necessary to induce changes in results produced by the model. The sensitivity analysis also contributes to decision makers understanding of the problem. Here small variations on the weight of each criterion were tested and a variation of an aggregated set of criteria was also studied.

In the particular case of the San Francisco Bay port changes considered reasonable produced no differences on the final result. This indicates that the model developed is capable of dealing with the problem in hands and it is ready to be applied to any given site.

This work was followed by and benefited from the support of the United States Corp of Engineering. The collaboration was essential since the very first step, the definition of the approach, but was also crucial for the research, the construction of the model and the application, members of the USACE acted as experts and decision makers.

The application of MCDA to the selection of dredging machines is still a field in development. Although the results obtained are very satisfactory and robust, it would be interesting to test and validate the model by applying it to other sites and projects besides the San Francisco Bay port. New applications lead to the collection of relevant information that could be used to improve the current model. The application to the San Francisco Bay port left out the criterion regarding externalities (g_4). Further research could include possible externalities and reconsider the benefits of each dredging machine.

During the application process the decision makers have shown no problems with the playing cards procedure. The selection of this technique was appropriate for the problem because of its simplicity, the imposed long distance communication made the application of a software inappropriate. Moreover, the rules of this procedure are easily understood and the decision makers can perform it by themselves later. The explanation and application of the swing weights procedure also occurred with no significant issues. This procedure can also easily be repeated by the decision makers if that is required for a better application to other scenarios.

The only possible limitation found in terms of growth was the fact that the method is already complex in terms of the amount of levels, criteria and dimensions considered. It is, however, possible to replace some of the existing criteria or dimensions for new ones if that proves to be the best solution.

The main question raised in the beginning of this project was related with the selection of the most suitable MCDA methodology to deal with this kind of project, site or scenario. Considering that the decision maker´s goal is to be able to rank any set of machines performing at any dredging site the most suitable methodology would be the one that would allow them to construct such ranking in a short amount of time and with no external help.

The Multi-criteria decision aiding model here applied to the San Francisco Bay port main contribution is the fact that it is complete, versatile and applicable to different settings.

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