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

Marta Gaspar

Department of Engineering and Management, Instituto Superior Técnico

Abstract

In the United States, the development and maintenance of water ways is essential to ensure and improve national and international trade. The construction and maintenance of water channels is based on the extraction of material from the bottom of the water courses. This activity is called *dredging*. In the US dredging activities are coordinated by the USACE, which ultimately decides where and how to dredge. The problem raised by the USACE is to develop a structured model that allows the selection of the most suitable machine for each site to be dredged. This work develops a Multi-criteria decision model to address this issue. The model delivers a ranking of the machines considered. The model was tested in the San Francisco Bay port and can be applied to any site and set of machines.

Keywords: Dredging, MCDA, Ranking, USACE

1. Introduction

Dredging is a complex practice with increasing importance all over the world. The performance of dredging activities involves careful and detailed planning in order to guarantee that the work is done in the most effective way. Each dredging project is unique. The selection of the best equipment to be used depends on a range of factors and information including the amount and type of material to be dredged, (USACE, 1983). The USACE (United States of America Corps of Engineers) aims to perform dredging activities in a sustainable way and in an economically efficient and environmental preserving manner. In order to achieve this goal it is essential to formalize the selection of the equipment.

This work addresses the need to develop a formal model that would rank, for each site, the available machines according to their adequacy to the conditions. Until now the selection of the equipment was based on information collected in the site, concerning essentially the purpose of the project, the characteristics of the sediment, intuition and previous experience.

2. Literature Review

In order to formalize the selection of the best dredging machine several methodologies can be used, namely optimization and/or simulation based techniques, simple holistic pairwise comparisons of alternatives, or MCDA (multi-criteria decision analysis). MCDA was selected due to its capacity to aggregate and deal with all types of data; it is also usable under conflicting interests. Several MCDA methodologies can be used. After weighting the advantages and disadvantages of each alternative, an *MCDA integrated approach* was selected. The methodology must deal with data from different sources. The *MCDA integrated approach* is able to aggregate information and deliver a recommendation. The application of an integrated approach that considers both the theoretical concepts and the application, is able to take advantage of the strongest points of each approach and is able to identify the similarities between them, it is the key for the presentation of the single solution. Here the focus will be on the integration of different methodologies in order to structure, and define the formal model. In 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. No matter the approach followed, the structuring of the decision problem in terms of alternatives and criteria is always done. Every approach envisages the identification of efficient alternatives, although through ways that can vary significantly. In the application of an integrated approach, irrespectively of principles and techniques, the methodologies use each other's outcomes as inputs (Belton *et al.,* 2002).

In order to develop the model it was essential the collaboration of a team of experts from the USACE, this team, formed by Engineer Matthew Bates, Engineer Cate Fox-Lent and Engineer Zachary Collier, produced for all questions a single consensual answer.

3. Model development

The development of the model starts with the definition of 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 original, also called primary, scales or metrics. Each criterion is constructed from at least one dimension.

Three FPV were identified. The first FPV (*environment*) deals with the negative impacts on the environment caused by dredging activities; the second (*economical*) includes all known costs and externalities of a dredging project and negative cash flows, and the third (*technical*) will analyze the technical requirements of the dredging project.

The first FPV is operationalized by the minimization of criterion 1, impact on organism (g_1) and minimization of criterion 2, impact on habitat (g_2). For g_1, two dimensions were considered: biological abundance (c_1) and impact on spawning behavior (c_2). The elementary consequence c_1 is assessed using a purely qualitative fifteen-level scale. The levels are based on the ACFOR (**A**bundant, **C**ommon, **F**requent, **O**ccasional and **R**are) scale, E_1 = {species are rare, species are occasionally present, species are frequent, species are common, species are abundant}. Each of the fifteen levels presents the initial evaluation of the abundance of species and the predicted final abundance. The levels are ordered according to their severity. The worst level involves a switch from species that are abundant before dredging is performed and rare afterwards, and the best level indicates that species are abundant both before and after dredging is performed.

The second dimension, impact on spawning behavior, uses a ratio between adults and new born. The impact is classified using one of five levels, E_2 = {very severe impact, severe impact, acceptable impact, soft impact, very soft impact}.

The combination of the available levels of dimensions 1 and 2 results on the 75 alternative levels for criterion 1. The levels were also ordered in descending order of impact, strongest-weakness. The ordering was based in one simple rule: levels should be ordered according to the severity of the impact; a two levels change in the impact of dimension 1 is equivalent to one level change in dimension 2. This difference in importance is due to the concern of c_2 with the long term impact.

For g_2, four dimensions were considered, turbidity (c_3), noise (c_4), contamination (c_5) and oxygen reduction (c_6).

As 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, as it was performed for criterion 1. Here, however, the situation was more complex: 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 were to be associated with a five-level scale, it would result 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 analyze the whole set of them. It was then necessary to reduce the potential number of combination. The simplification method considers only a few key reference impact levels – the ones that are 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 sixteen possible combinations. For c_3, the water transparency can be considered acceptable or low, E_3 = {acceptable values of water transparency for the site, low values of water transparency}. For c_4, the noise can be considered acceptable or high, E_4 = {acceptable values of noise, high values of noise}. For c_5, the water contamination can be considered acceptable or high, E_5 = {acceptable values of water contamination, high values of water contamination}. For c_6, the level of oxygen can be considered acceptable or low, E_6 = {acceptable levels of oxygen, low levels of oxygen}.

It is expected that the behavior of each alternative is sufficiently different for the criterion to be valuable even with two-level scales. These levels were ordered according to their severity, all dimensions were considered equally important. The most severe case is represented by level LHHL, low value of water transparency, high value of noise, high level of water contamination and low level of oxygen. On the other side of the spectrum the least severe is level AAAA, acceptable values of water transparency, noise, water contamination and oxygen. The complete set of results from the combination of the four dimensions is E_{g2} = {LHHL, LHHA, LHAL, LAHL, AHHL, LHAA, LAHA, LAAL, AHHA, AHAL, AAHL, LAAA, AHAA, AAHA, AAAL, AAAA}.

The construction of criteria g_1, g_2, g_5, g_6 and g_7 also follows this approach.

The second FPV is operationalized by the minimization of criterion 3, cost of dredging (g_3) and maximization of criterion 4, utility/externalities (g_4). For g_3, three dimensions were considered: dredging cost (c_7), transportation cost (c_8) and disposal cost (c_9). These dimensions are quantitative, presented in thousands of United States Dollar (K USD), and should be added up, resulting on the final value for the criterion. For g_4, two dimensions were considered: disposal externalities (c_{10}) and navigation (c_{11}). These are also quantitative dimensions, presented in K USD, and should be added up, resulting on the final value for the criterion.

The third FPV is operationalized by the maximization of criterion 5, adequacy of the equipment to the sediments (g_5), minimization of criterion 6, impact of the disposal method (g_6), and maximization of criterion 7, adequacy of the equipment to the physical conditions of the site (g_7). For g_5, two dimensions were considered: physical characteristics of the sediments (c_{12}) and quantity of material that needs to be dredged (c_{13}). For both dimensions, a five-levels scale was developed, the adequacy of the machines can therefore be classified as very bad, bad, acceptable, good or very good, E_{12} = {very bad adequacy, bad adequacy, acceptable adequacy, good adequacy, very good adequacy} for c_{12} and E_{13} = {very bad adequacy, bad adequacy, acceptable adequacy, good adequacy, very good adequacy} for c_{13}. The combination of the alternative levels of c_{12} with the alternative levels of c_{13}, results in the 25 alternative levels of criterion 5. For the ranking of the levels all dimensions were considered equally important.

For g_6, one dimension was considered: disposal method (c_{14}). This criterion´s scale will be equal to the primary scale associated with the dimension, a five level scale that classifies the adequacy of the machines to the disposal type as very bad, bad, acceptable, good or very good, E_{14} = {very bad adequacy, bad adequacy, acceptable adequacy, good adequacy, very good adequacy}.

For g_7, four dimensions were considered: dredging depth (c_{15}), distance to disposal area (c_{16}), physical environment (c_{17}), and production required (c_{18}).

For c_{15}, a dichotomously scale was developed: the machine can either be capable or not capable of performing at the required depth, E_{15} = {Yes, No}. For c_{16}, a three level scale was developed, the adequacy of the machines for the disposal distance can be bad, acceptable or good, E_{16} = {bad adequacy, acceptable adequacy, good adequacy}. For c_{17}, a three level scale was developed, the adequacy of the machines for the physical conditions of the site can be bad, acceptable or good, E_{17} = {bad adequacy, acceptable adequacy, good adequacy}. For c_{18}, a dichotomous scale was developed: the machines can either be capable or not capable of preforming at the required productivity rate, E_{18} = {bad adequacy, acceptable adequacy, good adequacy}. The combination of the alternative levels for each dimension generates the thirty six levels of criterion 7. For the ranking of the levels, all dimensions were considered equally important.

4. Application

Once all sets of levels have been identified, the differences between them should be quantified.

From the vast range of methods available to do such quantification an adaptation of the revised Simos´ procedure by Figueira and Roy (2002), also called the "playing cards" approach, was considered the most appropriate. More precisely, one version of this procedure proposed by Figueira (2014) was chosen. The choice was based on the fact that this version is particularly useful when the decision makers are not familiar with MCDA. In such circumstances, the decision makers can easily express their opinion and state the way they want to rank the set of levels. The score of each level is then defined 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 in 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 levels. The procedure can be divided into two phases. The first one, collection of the information, is performed with the decision maker. The second phase encompasses the computations that would result on 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.

The following two steps are then performed: firstly, using the set of cards with the name of each level, the decision makers are asked to rank the levels in ascending order, starting with lower values, usually related with more impact or worst adequacy, to higher values. Secondly, the analysis 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 a set of white cards. The number of cards assigned to a given difference between two levels should be proportional to the difference in importance of the two levels, a higher number of white cards should be attached when the difference in importance is bigger and a lower number of white cards should be assigned whenever the difference is smaller.

If no white cards are assigned to a given difference it means that the decision maker believes that the difference in the scores between the two levels can be used as a reference. If one white card is assigned it means that the difference between the levels is two times the settled reference, the difference corresponds to two positions. If two white cards are assigned it means that the difference between the levels is three times the settled difference, which corresponds to three positions. This procedure can be applied with as many white cards as the decision maker wishes. The number of positions is equal to the number of with cards assigned plus one.

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

The model here developed 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:

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

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 that precedes 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 computing the value of *p*, another formulation should be applied in order to assigned weights to all levels.

$$k_i = k_{i-1} + (p \times z_{i-1}) \qquad (2)$$

This procedure was applied for criteria g_1, g_2, g_3, g_5, g_6, and g_7.

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 decision makers 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 that should be assigned to the remaining levels the progression between them is considered linear.

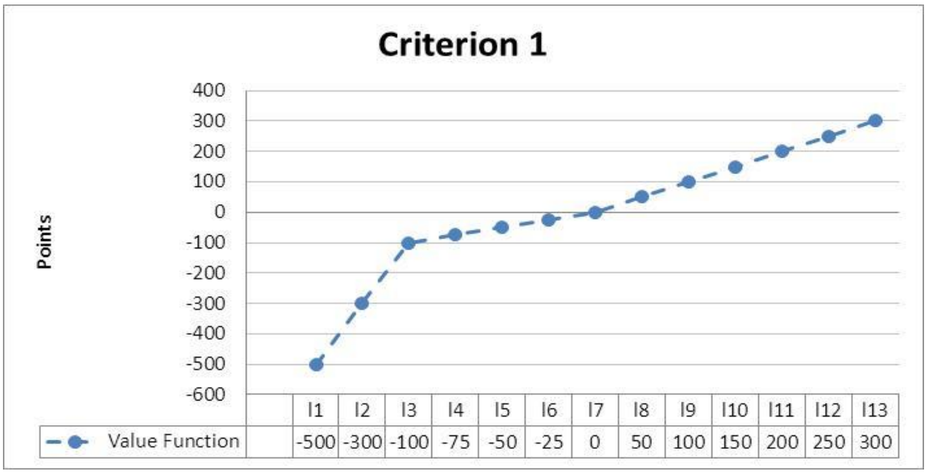
For criteria 1, the USACE considers level A_OO, which represents an acceptable impact on spawning behavior and no impact on biological abundance (the species that were before occasionally present would remain occasionally present), good. While S_OO, which represents a severe impact on spawning behavior and no change on the presence of the species, is considered neutral. The number of points that each position is worth is calculated using the model presented, equation below. The values assigned to the levels considered good and neutral are given.

$$p = 100 / \sum_{i=7}^{9-1}(z) = 100 \qquad (3)$$

$$K_2 = k_1 + [100 \times (2)] \Leftrightarrow k_1 = -500 \qquad (4)$$
$$K_3 = k_2 + [100 \times (2)] \Leftrightarrow k_2 = -300 \qquad (5)$$
$$K_4 = k_3 + [100 \times (2)] \Leftrightarrow k_3 = -100 \qquad (6)$$
$$K_5 = k_4 + [100 \times (1/4)] \Leftrightarrow k_4 = -75 \qquad (7)$$
$$K_6 = k_5 + [100 \times (1/4)] \Leftrightarrow k_5 = -50 \qquad (8)$$
$$K_7 = k_6 + [100 \times (1/4)] \Leftrightarrow k_6 = -25 \qquad (9)$$
$$K_7 = 0 \qquad (10)$$
$$K_8 = k_7 + [100 \times (1/2)] = 50 \qquad (11)$$
$$K_9 = 100 \qquad (12)$$
$$K_{10} = k_9 + [100 \times (1/2)] = 150 \qquad (13)$$
$$K_{11} = k_{10} + [100 \times (1/2)] = 200 \qquad (14)$$
$$K_{12} = k_{11} + [100 \times (1/2)] = 250 \qquad (15)$$
$$K_{13} = k_{12} + [100 \times (1/2)] = 300 \qquad (16)$$

Figure 1 shows, the function that results from the assignment of points to all the different levels in this criterion. It is possible to observe that the initial gradient is higher than the average gradient, meaning that degradation impact of the environment when the environment is already weakened is worse than the same impact when the environment is healthy.

Figure 1 – Value Function



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 uses the swing weights procedure (Goodwin & Wright, 2009). The application of this procedure was performed with the collaboration of the USACE´ s team of decision makers.

This procedure is based on the capacity of the decision maker 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. That is, the decision maker is asked the following: If you could choose one criterion to change from the least preferred level to the most preferred level what criterion would that be? And which criterion should be chosen in the second place? These questions are repeated until all the criteria have been 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 criterion that should occupy the last position of the ranking is the one that was picked in the last place.

Once all the criteria are ordered and the ranking is completed, the decision maker helps 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 maker is 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 is repeated until all the 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. In the end, the original percentage weights are normalized.

For example, 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.

Table 1 presents the values obtained for the normalized weight of each criterion.

Table 1 – Normalized weights assigned by criteria

Normalized weights	
w_3	25,5
w_1	23
w_5	19
w_7	12,5
w_6	12,5
w_2	7,5
Sum	100

To compute the overall score for each machine it is necessary that for each criterion one level has been assigned. These levels are translated into a number of points.

By machine, the overall score is the weighted sum of these points. Higher scores mean better performances.

5. Results

For test and validation the model was applied to a project in the San Francisco Bay port.

The San Francisco Bay port has a wide area and the conditions are not homogeneous throughout the entire region. An estimated total of 10,000 cubic yards of sandy material needed to be dredged; the disposal would be performed using open water placement at the San Francisco Channel Bar, which is 3 nautical miles away from the mouth of the Bay. It was also settled that the project would respect the EWs (Environmental Windows) 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 them together better.

The evaluation was performed for a set of five types of dredges: cutter-suction, dustpan, water injection, clamshell and dipper.

For each machine, seven levels, one for each criterion, were assigned. These levels indicate how well the machine performs vis a vis the criteria. Using the weighted additive model the overall score of each machine was calculated. Table 2 presents the resulting ranking:

Table 2 – Ranking of the alternative machines for the San Francisco Bay port scenario

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

For the specific conditions of the San Francisco Bay port, the model shows that the cutter-suction dredges ranks first. The score computed for this machine is twice the score obtained by the dipper dredges, the second in the computed ranking. The over 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 across the whole range of criteria, its weaknesses coming from the impact on environment and the impact of disposal. The cutter-suction does neither present the best technical performance nor the cheapest price, but it is the equipment that shows an overall best score.

Two of the machines tested turned out with very low overall scores, negative points in fact. These alternatives - dustpan and water injection dredges - are not adequate for the specific scenario considered. Their characteristics could prove useful in a different scenario, though.

The dipper dredges are the best technical alternative for the site and have little environmental impact on habitat and on environment. However, it 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 with cutter-suction dredge.

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

The model helped weighting the criteria and reaching the overall score of each equipment. It may be replicated to other sites. Different sites and another set of machines would imply a new ranking.

For the San Francisco Bay port, the USACE should consider using a cutter-suction dredger, the machine with the best overall performance.

The results obtained were subjected to sensitivity analysis to verify their robustness. It is important to test if the ranking initially obtained remains unchanged to variations on the weights assigned to each criterion. It was assumed that the “error” on the assignment of the points would never be over 10%. Therefore, for each criterion, an increase and a decrease of 10% of the points assigned by the decision maker was introduced. In order to further test the results, the needed weight´s value for the ranking to be altered was calculated. The criteria are tested one by one and the remaining weights are recalculated keeping previous relative importance. These analyses showed that the top three alternatives didn´t change even with very high variation on the weights assigned; proving that the results obtained are very robust.

A final aggregated test was also performed. The criteria were divided into groups. This division is useful to test changes in a subset of criteria - in this case, the technical and the non-technical criteria. For this analysis all the non-technical criteria were eliminated, impact on organisms (g_1), impact on habitat (g_2) and cost of dredging (g_4). This 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). The assumption was 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. The cutter-suction loses the first place in the new ranking, overtopped by the dipper dredges. 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.

The model proved robust. It is able to produce conclusive rankings even with imperfect information. Further application of the model would lead to the identification and correction of the criteria and the weights assigned.

6. Conclusions

The research here developed completed the work that is performed every day by the USACE. All the information was organized and the model created is now able to produce rankings of the available machines independently of the dredging scenario.

This work, being the result of an integrated approach, is also an example of how to apply MCDA to problems involving a great amount of data for different sources and conflicting interests.

The application to the San Francisco Bay port suggests that the steps followed can be easily repeated by members of the USACE.

The application of MCDA to the selection of dredging machines is still a field in progress. Although the results obtained proved very robust, it would be interesting to test and validate the model by applying it to sites and projects other then San Francisco Bay port. New applications of the model lead to the collection of relevant information that can be used to improve the current model. The application to the San Francisco Bay port left out the criterion regarding the externalities (g_4). The inclusion of externalities and indeed of the complete set of criteria would make it possible to fully grasp the benefits of each dredging machine

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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