Integration of environmental sustainability and product quality criteria in the decision-making process for feeding strategies in Seabream aquaculture companies

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ABSTRACT:

Economic criteria have traditionally been taken into account as the most important factor for the selection of the most suitable feed in aquaculture. However, currently, management decisions have become increasingly complex, taking into account issues such as environmental sustainability and product quality. In this regard, there is growing recognition that the quality of the environment in which an organization operates has a direct effect on its financial results. Unfortunately, the complex integration of all these factors, which are sometimes opposing, limits the ability of aquaculture producers to adapt their production strategy to cleaner production systems. In this context, the aim of this work is to address this problem with the development of a novel, multiple-criteria decision-making optimization methodology that allows producers to include different preferences in the design of feeding strategies. Here, this methodology is applied to gilthead seabream production. The results obtained show the utility of this methodology for integrating numerous criteria in the evaluation of various alternatives and for carrying out an efficient sensitivity analysis which test the impact of different hypotheses on stakeholders' preferences.

Keywords: *Clean production; environmental management; multiple-criteria; decision-making; feeding strategies; aquaculture;*

1. Introduction.

Aquaculture production has grown rapidly in the past few decades, as there has been an exponential growth in production to fill the gap between seafood supply and demand. However, this rapid development has not been without difficulties, among which the increase in the complexity of management stands out. Aquaculture farmers face many difficult decisions based on different biological, environmental and economic factors in their daily work, which has led to inefficient management, especially in small and medium-sized enterprises. Over the past few decades, several studies have addressed this constraint by applying optimization techniques and bio-economic models (Llorente and Luna, 2016; Besson et al., 2016). These studies represent a significant advance in the efficient management of aquaculture production, but there is still room for improvement. Currently, the use of optimization methods among managers who are not experts in this field is still low and the data processing power is, sometimes, insufficient. Furthermore, producers should take into account cost efficiency as well as environmental responsibility and product quality, aspects that can sometimes be in conflict.

In recent years, applying management tools and Decision Support Systems (DSSs) has received increasing attention. These tools provide expert information in an easy-to-use manner to end users. These tools have been mainly directed towards the integration of safety (Conte and Ahmadi, 2010) and biological (Bourke et al., 1993) issues in operational decision-making processes or to help make strategic decisions, such as site selection (Stagnitti, 1997) and facility design (Ernst et al., 2000). Furthermore, these tools have helped in economic aspects (Halide et al., 2009; Cobo et al., 2018), but to a lesser extent. The most recent contributions to the improvement of management capacity have been a result of technological advances in Big Data and Artificial Intelligence. These advances have allowed researchers to develop specific tools related to the development of real data collection and control systems (Zhang et al., 2014; Zhou et al., 2018).

In addition to foraging, aquaculture farmers began to have the need to adapt their management behavior to changing market realities and new regulations that place value on other production methods, with additional demands in terms of environmental sustainability and product quality. In response, cleaner production (CP) processes allowed businesses to visualize the concept of environmental sustainability in practice as a process of continuous improvement, which aims to efficiently use natural resources, reducing environmental impact and generating economic benefits

(Canal Vieira and Gonçalves Amaral, 2016). This shifted the emphasis to pollution prevention rather than pollution treatment (El-Kholy, 2002) and emphasized that the financial performance of an organization depends on the quality of the environment in which it operates (Porter and Kramer, 2006).

As a result, an increasing number of farms consider new criteria in the determination of production strategies. However, although eco-efficiency aims to attain a higher value with less input of materials and energy and reducing pollution, there is currently no widely accepted single indicator or index integrating these aspects of sustainability to enable the monitoring of an organization and relevant data on these factors are limited (Hens et al., 2018). Furthermore, most studies in this regard are focused on the effects on the environment of aquaculture production methods (Jegatheesan, 2007; Samuel-Fitwi, 2012; Cui and Chui, 2017) and do not analyze its integration with various criteria, such as economic considerations. However, these criteria have different relevance for each manager according to stakeholders' preferences, regulations and raw material cost, which makes the process very complex. This leads to a lack of methodologies and tools for producers to incorporate environmental management processes into their daily management hampering the development of ecological aquaculture, among other fields.

In order to address this issue, the present work applies multi-criteria decision-making (MCDM) optimization techniques to the determination of the optimal feeding strategy and considers the interrelationships between economic, environmental sustainability and product quality criteria. Feeding decisions and strategies in aquaculture are of great importance because feed is the main production cost in finfish aquaculture, which can account for 30%–70% of total production costs (de Verdal et al., 2017). Moreover, previous studies, such as Denham et al. (2015), have found that when measuring the carbon footprint of the aquaculture sector, feed has the greatest impact, predominantly generated by the energy consumption and the ingredients and quantity used, and the authors of this study highlight the potential of CP systems to reduce this impact. However, most studies apply MCDM methodologies to different strategic decisions related to aquaculture, such as site selection (Dapueto et al., 2015; Shih, 2017), planning of regional aquaculture development (El-Gayar and Leung, 2001), and diet formulations (Criste et al., 2016).

Therefore, the proposed model is a novel advancement that allows managers to include their own considerations in the task of exploring the whole range of possible feeds to find the most suitable one. The use of MCDM techniques in this situation is ideal because it is a problem with many possible solutions based on numerous factors for which subjectivity cannot be totally eliminated.

2. Materials and Methods

To find an optimal feeding strategy, a methodology has been established with a structure based on steps to standardize the decision-making process from beginning to end, which has been generally described in several studies of MCDM, such as Estévez and Gelcich (2015). In this decision context, four specific steps have been developed (Fig. 1): First, it is essential to clarify the problem and develop a database in which all relevant information for decision making is stored (2.1). In this regard, a hierarchy value tree of various criteria is developed depending on the objectives of the stakeholders (2.2). A bio-economic model of the process of farming in sea cages is then integrated for the estimation of various factors (2.3). Then, the fattening process is simulated for each feeding alternative, generating values for each criterion for the available feeds. Last, two MCDM optimization techniques are employed (2.4) to measure the relative importance of the criteria, using the traditional Analytic Hierarchy Process (AHP) (Saaty, 1980) and ranking the alternatives according to the Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981).

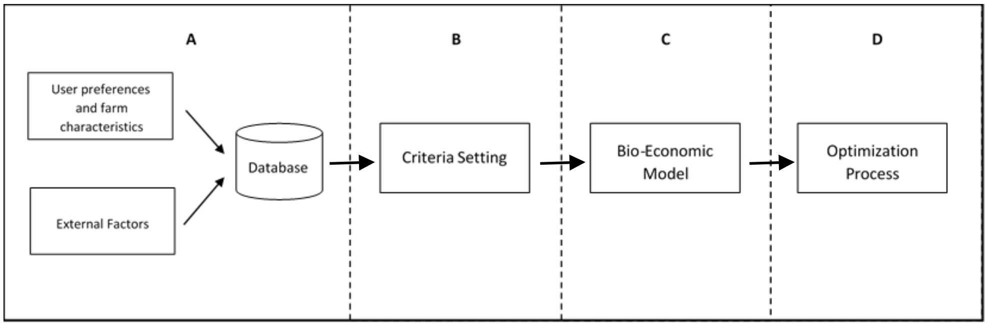

Fig 1. Software architecture according to the methodological approach.

Two open source solutions, the MySQL database management system and Python programming libraries, have been used to implement decision support software with the structure shown in Figure 1. These solutions make the process easily reproducible and adaptable to different environments.

2.1. The Database

The large number of data from various sources and the complex relations when it is integrated with the model make the development of a relational database necessary. The structure of the database (Fig. 2) consists of a central axis, which identifies the aquaculture farm and its main characteristics, and four groups of tables. First, two of the groups include information about the current characteristics of each cage and the specific rates of feeding, growth, loss and dispersion according to these characteristics and the available feeds. The last two groups represent the exogenous factors that affect the production. These cover the values for the uncontrollable variables, which cannot be manipulated by the decision maker, but do affect the system performance, and therefore are required for forming a reliable decision (Casini et al. 2015). These four groups are composed using the following information:

a. <u>Technical data of the farm and its cages</u>.

   This information represents the number of cages, their current state and characteristics and the fish fingerlings origin. The fingerlings table includes the specific species and strains, which allow the producers to explore the future performance of these under different conditions and feeds, and the price of the product in the market according to weight and time.

b. Feed information.

These tables include the feeding, growth, and mortality data, and the information of constituents of and contaminants in the feed, which is provided by the manufacturer or directly measured by the producer. Because some rates can vary depending on certain aspects, such the growth rate depending on the origin of the fish fingerlings, the methodology developed allows the producer to fill in the database with the appropriate data depending on the fish strain, origin, or the availability of specific feeds for the species produced and, if possible, to use specific functions based on their own empirical information of feeding, growth, loss, and dispersion

c. Fish market.

These tables include the general characteristics of the fish species and the market expected, such as weekly sale prices either in the market or agreed to with a customer. It additionally allows for consideration of different sale prices according to fish size and type of production.

d. Environmental conditions.

Environmental data include the temperature of the farm on a monthly, weekly, or daily basis and measures of current oxygen and salinity, if necessary. These can be obtained through the producer collecting this information or through publicly available measurements.

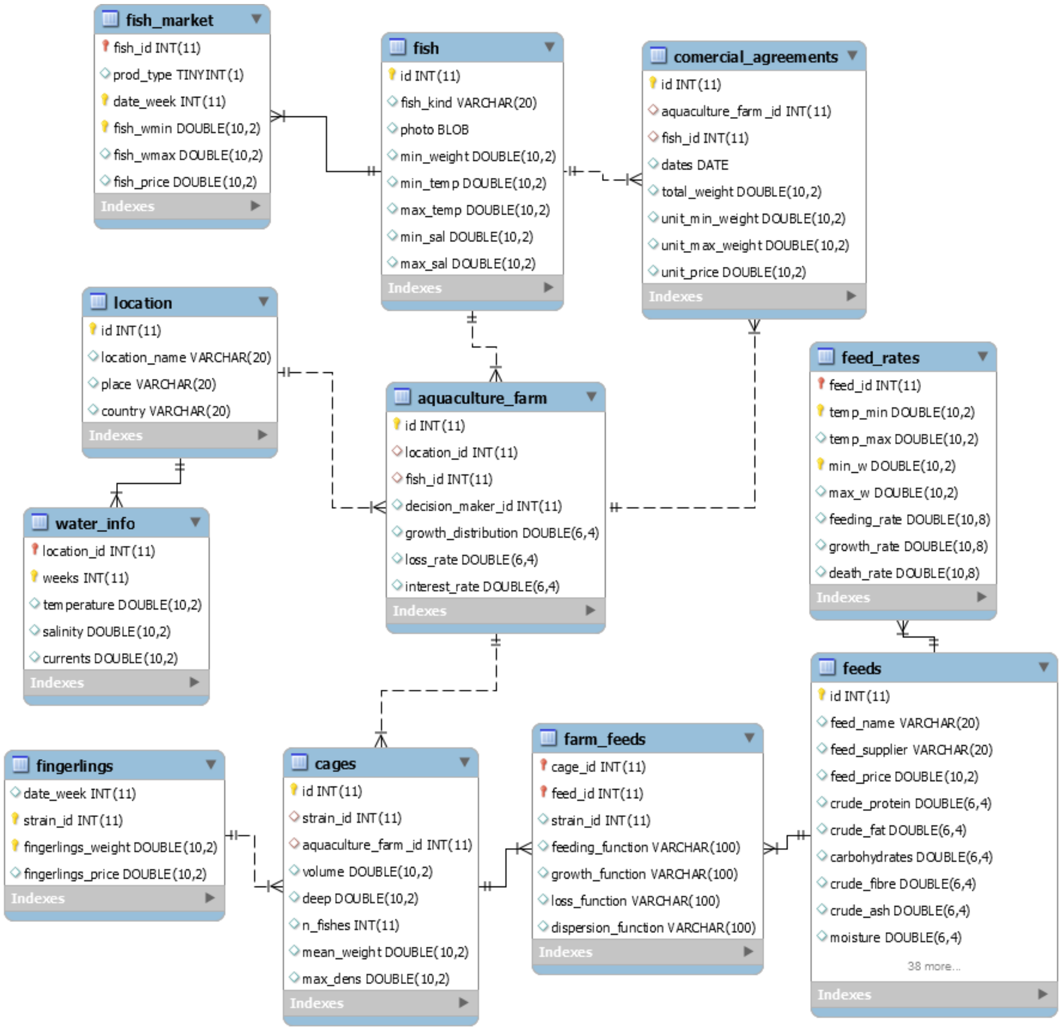

Fig 2. Entity-relationship model

2.2. Criteria setting

This section presents the three categories (economic factors, environmental sustainability, and product quality) used for choosing the most suitable feed and discusses different criteria that could be included inside each one, according to the specific data and needs of the user. Effectively, decision makers could choose some of these factors for consideration or add new criteria before ranking them according to their individual needs.

2.2.1. <u>Economic criteria</u>

From a conventional economic point of view, the main objective of aquaculture enterprises is profit maximization. In this respect, an economic sub-model has been included to estimate the operational profit by taking into account the revenue obtained from the sales and the costs incurred in the feeding process.

First, the revenue is calculated as a function of the average mass, its expected dispersion, and the market price in dollars per kg. The total weight in the cage is directly influenced by the growth, dispersion and mortality rates, so it will depend on the selected feed and the variations inherent to the fish source and species. Market prices considered are based on commercial classes, seasonal price and type of production (e.g. conventional or organic). Then, the operating profit is estimated using only the feeding costs, making the assumption that in the other work costs are not influenced by the chosen feed and so do not change the value of the economic criteria. For further analysis, the effects of additional operating costs could be taken into account.

2.2.2. Environmental sustainability criteria

Sustainable and organic aquaculture production procedures constitute an alternative to conventional aquaculture, reducing the negative environmental impacts of production procedures focused only on cost reduction. In this regard, the reduction of some contaminants and fish-derived products through better feeding practices usually represents the major concern, but feed production is a key determinant because it uses energy and emits carbon dioxide, which people in aquaculture industry should strive to minimize. (Boyd, 2015).

However, producers sometimes perceive some risks, mainly in the short-term, resulting from higher organic and sustainable feed prices or greater uncertainty in terms of regulation and selling prices, which causes the number of farms applying these new forms of production to be lower. Several studies, such as Bostock (2010), have identified the need more politic impulses to bring realistic external costs of environmental services into company accounts to promote a real change to ecologically sustainable aquaculture.

With regard to that uncertainty, research studies on consumer preferences indicate that some ecological aquaculture labels have an impact on purchasing decisions, but these products are not well-recognized and even less trusted by customers (Risius et al. 2017). In order to address this issue, official ecolabels have been designed to simplify this process and certify organic products from a trusted third party, which involves a disadvantage for the high costs of certification processes. For the producers involved in organic production and labelling of organic products, the Commission Regulation (EC) No 889/2008 of 5 September 2008 and its various amendments have set specific rules on feeds for carnivorous aquaculture animals. They shall be sourced by products from: organic aquaculture, fisheries certified as sustainable or organic feed materials of plant origin (60% maximum). Furthermore, there are numerous restrictions that directly affect the economic development (e.g. the maximum stocking density of 15 kg/m^3 for sea bass and seabream).

In contrast, there are growing concerns about the long-term effects of some decisions on the environment surrounding aquaculture farms. In this regard, many consumers and producers prefer other sustainable strategies. With regard to feeding strategy, Lembo et al. (2018) showed that in order to minimize the environmental impact of aquaculture, stakeholders placed the highest value on the prevention of chemical, namely nitrogen and phosphorus, on antibiotic dispersion in the natural environment and on the increase of feed efficiency in terms of fish meal and oil used, despite these not being clearly regulated.

Along these lines, the process of feed fabrication and transport consume the majority of the energetic input and produce the majority of emissions (Pelletier and Tyedmers, 2007). Therefore, prior to the arrival to the farm, the environmental impact of feed production could be also a crucial criterion when choosing a feed. Some of the most commonly used factors are the energy use (MJ equiv.), which is traditionally applied to compare the energy consumption of processing the feed ingredients and obtaining them, and the global warming potential impact (CO_2 equiv.) of the greenhouse gas emissions (Draganovic et al., 2013; Abdou et al., 2017), among others.

Consideration of these factors has led to the generation of a large amount of literature on Life Cycle Analysis of aquaculture production in specific cases, such as Mungkung et al. (2013). Likewise, this field has generated a need for tools enabling the inclusion of specific criteria depending on producers' preferences and integrated analysis of the chosen factors to improve the overall efficiency of the farm.

2.2.3. Product quality criteria

When seafood is consumed, its quality is perceived by the appearance, odor, flavor, and texture. The assessment of these quality factors of aquaculture fish has been analyzed in numerous scientific studies, such as those included in Alasalvar et al. (2011), and has increased in recent years with the increase of plant oil-based feeds. However, it is still very difficult to contemplate objective criteria in this area. For this reason, only two criteria have been included as an approach to two different points of view about the use of feed components to maximize the organoleptic characteristics of the fish and, hence, the perception of quality.

First, as Shahidi (2011) explains, there is a rapidly growing interest in fatty acids, particularly omega-3, as health-promoting dietary components, and the best source of them is fatty fish. In this respect, some feed producers have conducted empirical studies feeding fish during the fattening process to approximate the final amounts of omega-3 fatty acids. On the basis of this groundwork, an estimation of omega-3 transmission has been included as a feed quality criterion.

In comparison, re-feeding fish that previously received plant oil with diets containing fish oil over a period of 90 days could be adequate to almost fully restore the initial muscle fatty acids in both gilthead seabream and sea bass (Grigorakis, 2011). This has allowed producers to use plant oil in the early stages and balance the amount of fish-based feed afterwards. As fatty acids are the one of the main pre-harvest factors affecting quality, the amount of fish-based feed that is used in the last months of production has been included as a criterion.

There are several studies that analyze genetic and environmental factors including salinity, current, and temperature (Rasmussen, 2001; Cordier et al., 2002). These factors have the potential to Influence the quality of the product.

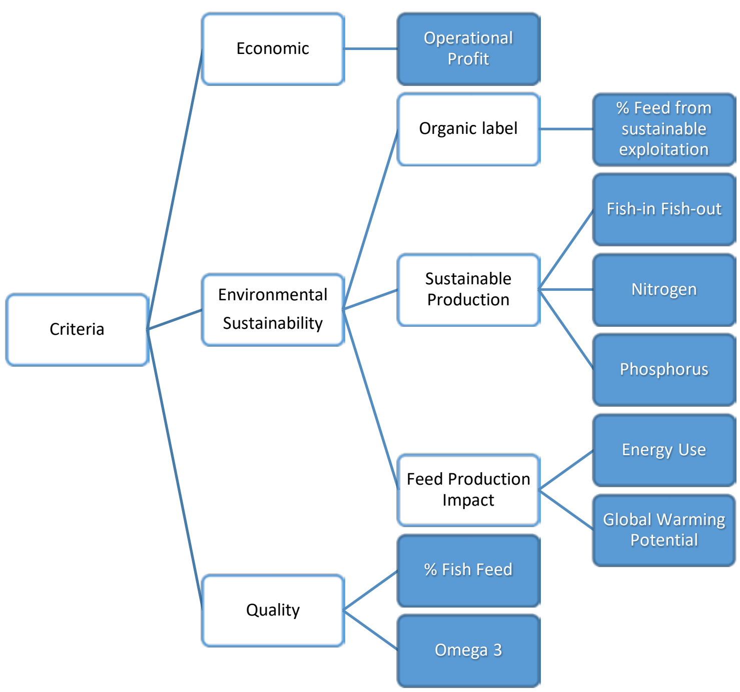

Fig. 3 Criteria hierarchy – tree structure: Highlighted boxes correspond to finally included criteria[1]

[1] The Fish-in Fish-out ratio represents the feed efficiency, measuring the amount of fish based feed needed to produce a unit weight of the cultured species.

2.3. Bio-economic model

Once the criteria have been established, the bio-economic model estimates the results or consequences of each alternative, taking the characteristics of each feed and simulating all of the processes during a specific period. This model has been already described in previous studies developed by Llorente and Luna (2013, 2014) and Cobo et al. (2015) integrating a biological model of the process of farming in sea cages with an economic model that quantifies the operational profit. The biological model considers feed and growth rates as a percentage of the weight of the fish, depending on weight and environmental conditions. The economic model uses the expected revenue and the feeding cost incurred during the farming period to estimate the final operational profit.

However, new technologies and MCDM techniques allow the model to take into account more factors, such as the product quality or factors that cause a negative effect on the environment. This is an improvement in the model that presents the decision-making process in aquaculture as a problem with various possible solutions depending on the influence over environmental or quality aspects when deciding the best production method. The value for these factors is estimated from the composition of the feed selected by the producer and the total amount consumed. Therefore, the feed composition and quality are considered crucial variables in the present study.

In this regard, the model takes the assumption that producers cannot address the control of any of the abiotic factors affecting the growth process, such as temperature, light, salinity, and oxygen, in an economically efficient way (Brett, 1979). However, several assumptions have been made:

a. Currently, the model considers only one-time investment, although the methodology is adaptable to a DSS that considers an infinite series of investments.

b. During the fattening process, only one feed can be used. Actually, this assumption may need to be addressed in the future because some farmers change the feed during the colder months to try to maintain favorable growth and mortality rates.

c. The producers will make the decision of when to harvest based on their economic needs or agreements, so harvesting weight will be slightly different for each feeding strategy.

d. Although main rates can be calculated from the manufacturer's information depending on the environmental conditions and the size of the fish, this methodology allows the producer to introduce specific functions based on empirical findings in aspects such us feeding, growth, loss or dispersion according genetic, source or dietary aspects.

On this basis, taking the information acknowledged by feed suppliers or directly measured by producers and its interaction with external factors for each farm, the fattening process is simulated for each feed, generating values for each criterion as the information is available. Additionally, the developed methodology and database used allow decision-makers to consider, when such data is available, fish sources as a variable that directly affects the results of these alternatives, thus multiplying the number of values obtained for each criterion.

2.4. Optimization process

Prior to the final selection of the most suitable alternative, establishing the relative importance of the different objectives is fundamental to any MCDM method. In this way, a MCDM optimization technique is applied in two steps: (1) measure of the producer perception about the relative importance of each criterion and (2) selection of the feed that provides the most convenient results for the producer by its closeness to the ideal solution.

2.4.1. Weighting the criteria

In real situations, it can be very difficult for the decision makers to express their subjective preferences about various criteria and measure them. To deal with this situation, an application of the Analytic Hierarchy Process (AHP) has been developed based on Cabral et al. (2016). The traditional AHP is widely used for solving MCDM problems, turning human judgements into exact or fuzzy numbers (Chan, 2007).

In this regard, the AHP organizes the criteria into a hierarchical structure and compares them by pairs, scoring each criterion related with another one rather than quantifying it directly (Table 1). This makes it easy to integrate different subjective measures into a final weight for each criterion.

Intensity	**Importance of one over another**	**Explanation**
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience or judgement slightly favors one criterion over another
5	Essential or strong importance	Experience or judgement strongly favors one criterion over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible.
2,4,6,8	Intermediate values	When compromise is needed

Table 1: AHP Marks Interpretation - Saaty (1987)

With this aim, this methodology creates a matrix associated with each hierarchical level of criteria, where each entry a_{jk} represents the importance of the j_{th} criterion relative to the k_{th} criterion (Eq. 1). The pairwise comparison values stored in the matrix are then aggregated to form a vector of relative weights for each criterion considered in the matrix. (Ivanco et al., 2017)

In order to calculate the weights that the AHP model will assign to each criterion, different alternatives have been proposed in the literature. One of the most popular is Saaty's approach, which calculates the weight vector as the normalized components of an eigenvector corresponding to the largest eigenvalue of the matrix.

$$C^{P_i} = \begin{bmatrix} 1 & a_{12} & \dots & a_{1m} \\ 1/a_{12} & 1 & \dots & a_{2m} \\ \dots & \dots & 1 & \dots \\ 1/a_{1m} & 1/a_{2m} & \dots & 1 \end{bmatrix}$$

Eq. 1: Pairwise Comparison Matrix

AHP additionally estimates a measure of the consistency in the decision maker's judgements (Wang et al., 2007).

2.4.2. Feed ranking

In the second step, a fitness function *F(X)* is built for each feed taking the Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) methodology as a reference (Hwang and Yoon, 1981). This technique is based on consideration of two hypothetical alternatives: the positive-ideal (with the best values for all of the attributes) and the negative-ideal (with the worst values for all of the attributes), and applies a fitness function (Eq. 2), which is defined as the relative closeness to the ideal solution:

$$F(X) = \frac{d^-(X)}{d^-(X) + d^+(X)}$$

Eq. 2: Fitness Function

where $d^-(X)$ and $d^+(X)$ represent the separation of criteria values of *X* from the negative and positive ideal solutions, respectively. This ratio varies between 0 and 1, and alternatives with a ratio closer to 1 are preferred.

Finally, a ranking of the alternatives is presented, indicating which would be the most suitable for the producer. This ranking is included in a report with all of the information of each criterion and the final weekly distribution of revenues and costs.

3. Application to the culture of gilthead seabream in the Mediterranean Sea

To test the developed methodology a farm of gilthead seabream, which faces the choice for the selection of the optimal feeding strategy for a year in three different scenarios based on decision-maker preferences, has been simulated. For this analysis, the availability of three different feeds in the market is assumed.

The results were generated and are presented following the four steps to standardize the decision-making process developed in the methodological approach. Last, as a discussion of these results, a sensitivity analysis of the feed selection to minor changes in a farmer's judgements is carried out.

3.1 Decision problem

In order to simulate the MCDM methodology, it is necessary to start with the collection of relevant data. In the present case, the specific characteristics of the farm are based on those found in the Mediterranean Sea (Table 2):

a. Technical data of the farm represent a unique sea cage of Gilthead Seabream. Its capacity is 200 m^3, but the density depends on the type of production. It is assumed that the maximum biomass density is equal to the maximum insurable biomass density (20 kg/m^3) or to the maximum density allowed in the case of organic labelled production (15 kg/m^3), so the growth is unaffected (Luna, 2008). Fingerlings, which are on average 30 grams, are currently in the cage coming from the same source. They can only be sold when they are over the minimum weight of 300 grams.
b. The used weekly selling prices correspond to the main Spanish wholesale market prices for the commercial classes of Seabream (300–400 g, 400–600 g, 600–1000 g) in 2018. The prices are reduced by the average wholesale-producer margin, as stated by MAPAMA (2012) and used as a proxy of the ex-farm price. In the case of organic aquaculture, Zander and Feucht

(2018) have shown that the willingness to pay varies between 7% to almost 20%, depending on attribute and country. Therefore, the used price is on average a 15% higher than in classical aquaculture for the same period.

c. The environmental conditions were obtained from the oceanographic buoys network of the Spanish Port Authority, which covers the principal locations of marine aquaculture in Spain. It includes daily data of temperature, salinity and currents. Previous data are used as an approximation of next year temperature. The simulated conditions for the culture of gilthead seabream in sea cages are based on real conditions in a location of the Mediterranean Sea close to Tarragona registered over the last several years (Fig. 4).

Parameter	Value
Seeding Date	15/06/2018
Harvesting Date	15/06/2019
Time horizon	52 weeks
Maximum biomass density	20 kg/m3
Cage production capacity	200 m3
Juvenile weights	30 g
Feasible harvest sizes	(300, 1000) g
Location	Tarragona (2720)

Table 2: Farm Characteristics

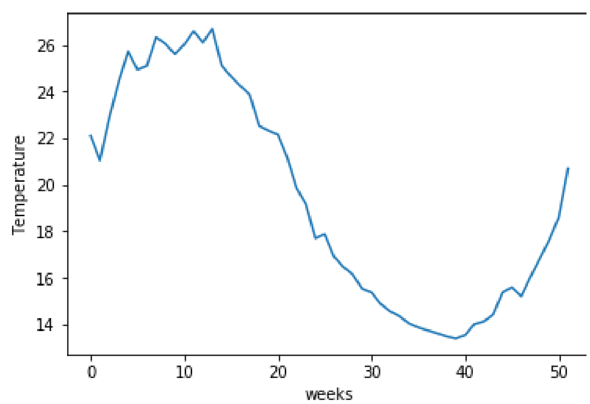

Fig. 4: Avg Temperature - Port Buoy 2720

3.2 Feeding alternatives

In the present case, the producer has three alternatives for feeds: Feed 1 (F1) a high-performance feed in terms of price-quality ratio in normal situations, Feed 2 (F2) a feed with higher costs but with better results specifically under cold conditions, and Feed 3 (F3) an organic feed entirely made with products from organic fisheries/production, which presents a higher cost and overall quality. At the initial moment, only the information shared by the feed manufacturer is available and, therefore, it uses feeding and growth tables depending on the environmental conditions and the size of the fish, as is in the DSS developed by Cobo et al. (2018). However, the developed methodology allows for changing these rates throughout the process.

With respect to the characteristics needed to estimate the values of the criteria, the main data is provided by the feed producer in relation to the feeding amount used during the farming period. However, there are insufficient data to estimate all of the theoretically proposed criteria because there is no information from the manufacturer about the feed production system. In this regard, feed production criteria have been estimated based on the study conducted by Pelletier and Tyedmers (2007), on which they presented the Life Cycle Impact Assessment results for different feed ingredients calculated as the sum of three stages: raw material production, processing and transportation. In this way, the value of Energy Use and Global Warming criteria has been calculated for each feed as the amount of MJ or kg CO_2 equiv. generated by one kilogram of each feed ingredient multiplied by the quantity of these ingredient used during the farming period.

Feed Info	F1	F2	F3
Price dollars/Kg	1.11	1.19	1.49
% Fish origin feed	25.0%	38.0%	55.0%
% Plant origin feed	50%	62%	45%
% Poultry origin feed	25.0%	0%	0%
% Organic Feed	0.0%	0.0%	100.0%
Total Nitrogen (g per kg of feed)	77.5	73.6	99
Total Phosphorus (g per kg of feed)	16.30	16.80	17.50
Energy Use (MJ equiv. per kg of feed)	19,451	9,422	24,815
Global Warming (kg CO_2 equiv. per kg of feed)	1,665	0,800	1,705
Omega-3 (g per kg of fish growth)	10.2	14.9	17.3

Table 3: Feeds info

3.3 Simulation of the results for each alternative

Once the criteria and the different alternatives have been established, the process starts with the simulation of the growth achieved weekly, the amount of feed used to achieve it and the potential revenue of this growth. Thereafter, the value of each criterion is estimated weekly, producing a trend throughout the farming period as an essential point of reference for the producer.

In this regard, growth and feeding amounts are estimated with the bio-economic model. For this, in the present study, a simplification is made, because of the lack of real data, in which the dispersion of growth is assumed to follow a normal distribution of the mean weight. This implies that the variables that are dependent on the total weight reached can be calculated directly using the total number of fish and their average weight. Then, revenue and costs involved are quantified, both in unitary and aggregated terms (Fig. 5). Based on this information, the nine selected criteria can be estimated, which makes it possible to comprehensively compare the three feeding alternatives.

The first result observed is how density, and therefore the number of fish, limits the capacity of the organic production to equal the results of the others. The number of individuals is the maximum that will allow the producer to keep the density below the limit, so it is calculated initially in relation to the type of production and the expected growth and death rates. The results show that, while F3 has the best results, the final profit of the farm is better with the selection of F2 or F1 feeds.

In economic terms, it can be determined that the first feed (F1) is the best choice under these conditions; it presents the highest profit, approximately $8.730, closely followed by F2, because of its capacity to reach the highest aggregated weight with the lowest cost per unit. However, the aim of this work is to take into account the consequences of more criteria, such as environmental and quality factors and to assess their interactions and test the variation in the final selection.

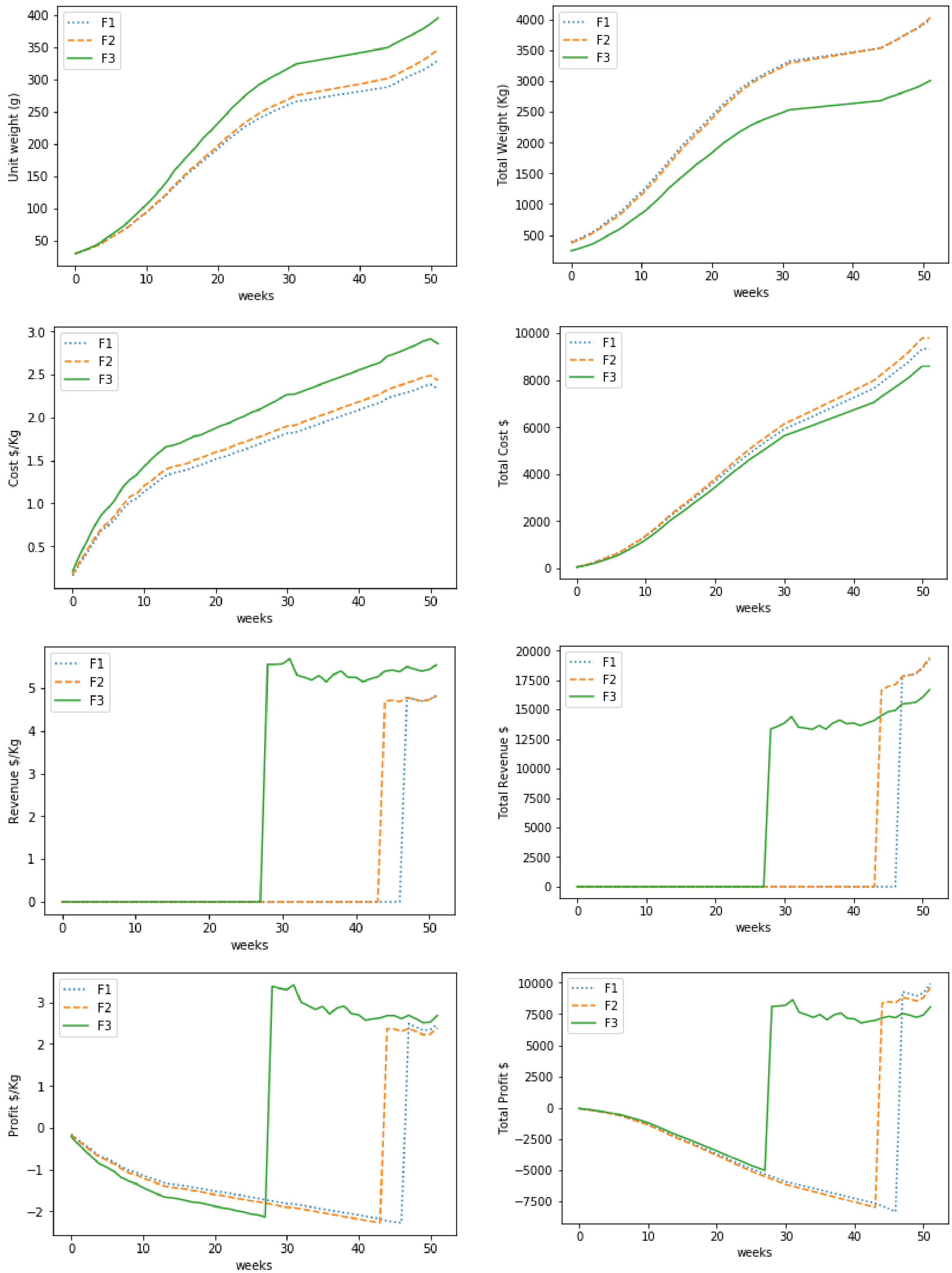

Fig. 5: Farm Evolution

With respect to the environmental sustainability criteria, several contradictory results should be highlighted. The F1 feed is the option that presents the lowest use of fish in feed (Fish-in Fish-out ratio), but F3 includes all its feed products derived from whole fish caught in fisheries certified as sustainable. This causes differences when measuring the effect of each alternative on its environment and supports the differences observed in the methodological approach between organic and sustainable production. Moreover, contaminant values are similar in all of the alternatives, but F3 presents slightly less pollution because of the lower amount of feed used during the process.

Finally, the higher ability of F3 to produce fish with better organoleptic characteristics is considered because it presents the best quality results both in the amount of fish feed used during the last months and the transmission of omega-3. The aggregated results for each alternative are presented in Table 4.

Measure	F1	F2	F3
Number of fish	12,141	11,619	7,606
Unit weight	329.28	346.71	395.40
Total weight (kg)	3,997.82	4,028.39	3,007.45
Cost ($)	9,341.17	9,796.42	8,596.02
Cost per kg	2.06	2.14	2.52
Revenue ($)	19,262.20	19,409.48	16,664.00
Revenue per kg	4.24	4.24	4.88
FCR_{total} (%)	210%	204%	191%
Economic Criteria			
Profit ($)	9,921.03	9,613.06	8,067.96
Environmental Criteria			
Organic Feed (%)	0%	0%	100%
Fish-in Fish-out	52%	77%	105%
Total Nitrogen (g)	650,069.23	604,280.52	567,337.66
Total Phosphorus (g)	136,724.24	137,933.60	100,286.96
Energy Use (MJ equiv.)	163,154,800	77,357,760	142,206,900
Global Warming (kg CO_2 equiv.)	13,966,000	6,568,266	9,770,815
Quality Criteria			

% Fish origin feed	25%	38%	55%
Omega-3 (%)	1.02%	1.49%	1.73%

Table 4. Main results after 52 weeks

The comparison of simulated results shows why MCDM techniques are necessary for aquaculture producers who want to introduce more than one criterion in their decision-making process. The complexity of the inclusion of these criteria is increased by the subjectivity and the opposition between some of them, impeding the ability to make decisions with traditional methods.

3.4 Criteria weighting and prioritizing alternatives

Next, the value of each criterion was estimated based on three theoretical scenarios of decision-makers' preferences when planning the feeding strategy in the described farm. The scoring process follows a hierarchical structure, starting from the comparisons of the three groups of criteria and ending on the disaggregated criteria of each group by pairs. This system reduces the number of evaluations to just the numbers under the main diagonal, with the others being able to be deducted by the property of reciprocity ($a_{ji}=1/a_{ij}$). After that step, the AHP methodology tests the consistency of the judgements and integrates their relative importance for the estimation of the overall weights.

The three scenarios considered are the following (Table 5): First, a traditional decision-maker with the main objective of maximizing the annual profit will, therefore, have minimum interest in the other criteria. Second, a scenario that simulates the perception of a person concerned by the economic performance of the farm, but aware of the environmental effects of farming. In this case, there is a greater balance between economic weights and those associated with parameters of environmental sustainability and product quality. Last, a decision-maker trying to differentiate the product with an organic label, ergo giving value mainly to the percentage of organic production fish in feed, as requires the European regulation, and to a lesser extent in the quality criteria.

Criterion	Weight - Scenario 1	Weight - Scenario 2	Weight - Scenario 3
Economic Criteria	**81.8%**	**58.7%**	**8.3%**
Profit	81.8%	58.7%	8.3%
Environmental Criteria	**9.1%**	**32.4%**	**75.0%**
% Organic Feed	0.3%	1.0%	48.2%
Fish-in Fish-out Ratio	3.2%	6.3%	5.4%
Total Nitrogen	1.0%	6.3%	5.4%
Total Phosphorus	1.8%	6.3%	5.4%
Energy Use	1.0%	6.3%	5.4%
Global Warming Potential	1.8%	6.3%	5.4%
Quality Criteria	**9.1%**	**8.9%**	**16.7%**
% Fish origin feed	0.9%	1.5%	1.9%
Omega 3	8.2%	7.4%	14.8%

Table 5: Final weights

Once the feeding alternatives and the final weight for each criterion in the three different scenarios have been analyzed, it is possible to implement the fitness function that sorts the alternatives in each scenario and chooses the best one. That fitness function F(X) is built for each feed by applying the TOPSIS methodology considering two hypothetical alternatives: the positive-ideal with the best value of the three available alternatives for each criterion and the negative-ideal with the worst values of the three available alternatives for each criterion (Table 6).

Criterion	Objective	Positive-ideal	Negative-ideal
Economic Criteria			
Profit ($)	MAX	9,921.03	8,067.96
Environmental Criteria			
Organic Feed (%)	MAX	100%	0%
Fish-in Fish-out Ratio	MIN	52%	105%
Total N (g)	MIN	567,337.66	650,069.23
Total P (g)	MIN	100,286.96	137,933.60
Energy Use (MJ equiv.)	MIN	77,357,760	163,154,800
Global Warming (kg CO_2 equiv.)	MIN	6,568,266	13,966,000
Quality Criteria			
% Fish origin feed	MAX	55%	25%
Omega 3 (%)	MAX	1.73%	1%

Table 6: Hypothetical ideal alternatives

Then, the relative closeness to the ideal solution is measured in a ratio between 1 and 0 and the alternatives are ranked according to their proximity to 1 (Table 7).

Scenarios	Criterion	F1	F2	F3
Scenario 1	Closeness	73.23%	67.89%	26.35%
	Ranking	1	2	3
Scenario 2	Closeness	59.49%	64.23%	33.73%
	Ranking	2	1	3
Scenario 3	Closeness	4.36%	6.28%	94.48%
	Ranking	2	3	1

Table 7: Closeness and final ranking

In the first scenario, where the economic criterion has the higher importance for both alternatives, F1 and F2 are much closer to the ideal solution than F3. More specifically, F1 feed is the optimal selection with a closeness of 73.75%. For the second scenario the first two criteria have similar closeness scores, but with F2 being slightly higher. The reason for this change in order is that, although in the second scenario the economic criterion is by far the most important, all of the criteria related to environment have great significance and the F2 feed is the least polluting one.

The F3 feed is the top ranking in the third scenario. In this case, the producer puts the most value in the organic requirement, and only the F3 feed fulfils it. For this reason, the closeness of the others is close to the minimum.

Finally, the development of this methodology in this type of systems allows the farmer to receive an automatic report, which includes not only the ranking of alternatives according to the importance given to each criterion, but additionally a guide with the values that make up the fattening process during the entire period. This report makes this simulation reproducible in a specific environment and allows the user to recalibrate the results according to the differences observed throughout the fattening process.

3.5 Sensitivity analysis

Our results show how important the inclusion of multiple criteria is in the decision-making process. However, it is additionally helpful to make a “sensitivity analysis” of the actual ranking of alternatives to test the consistency of the final decisions when there are minor changes in judgements. Furthermore, it can help decision-makers to make better decisions if they can determine how critical each criterion is (Triantaphyllou and Sanchez, 1997).

In the present work, the sensitivity analysis approach determines the smallest change in the current weights of the criteria, which can alter the existing ranking of alternatives. For this, the difference between the economic criterion and the other two is reduced, from the actual situation where the pairwise score of the economic criterion related to the other two is at its highest, to the point where all criteria have the same value (Fig. 6).

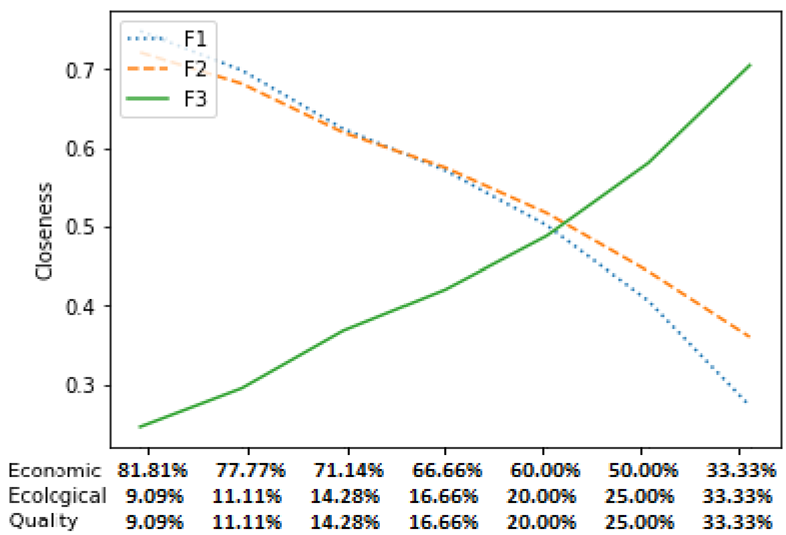

Fig. 6: Sensitivity analysis

This analysis shows that the selection does not change for small changes in weights, but it does for changes greater than 10%. Furthermore, although the closeness of the first feed alternative is much higher than the third one under the judgements of the first scenario, if the economic criterion decrease under the 60%, then the existing ranking of alternatives will change to an organic-labelled production. This confirms once again that the MCDM methodology is ideal for this type of situation because it allows the producer to select the optimal feed as well as shows the effects of small changes in preferences. This is especially useful in companies with several decision makers and diverse opinions.

4. Conclusions

Aquaculture has been the fastest growing animal production sector in recent decades. This growth has been mainly possible because of a high degree of technological innovation transforming the industry from traditional extensive production systems to industrial scale activity. This evolution has facilitated an increase of production efficiency, a reduction of production costs and an increase of the economic performance. However, the exponential growth of the activity has revealed several problems that are an issue for the sustainable development of the industry. Among these problems, the priorities given to the economic criteria and the quality stand out, as does the lack of consideration for environmental aspects in the decision-making processes.

In many cases, this gap is not caused by a lack of interest from producers, who are aware of the environmental impact of their activity, nor from the consumers and society in general, among which there is an increasingly greater awareness. The scientific community has worked to study and include the environmental considerations in aquaculture. However, the number of studies that address this problem from a multidisciplinary perspective is small. The complexity of the decision-making processes in production, resulting from the numerous criteria that affect the activity, has caused the environmental aspects to not be properly considered in the aquaculture industry. The lack of methodologies and tools to support decision-making, which allow for including environmental and quality criteria in the planning of production in an efficient way, while maintaining the economic sustainability of the activity, is still a barrier to the development of environmentally sustainable production.

This work aims to contribute novel and valuable methodology of integration of different criteria in the decision-making process; to consider the demands from the markets, economic efficiency, environmental responsibility and product quality. This methodology has been applied to the selection of the most suitable feed because this factor accounts for a large part of aquaculture companies cost structure and to the major environmental concerns because of the relatively recent increase in use of pelleted feed in modern aquaculture (Edwards, 2015). Our results show the practical utility of this methodology to integrate different criteria and how new ways of production involve different feeding choices.

The existence of a methodology that combines, environmental, product quality and economic criteria in the management of aquaculture farms will allow producers to analyze the economics of sustainable farming. In addition, it will allow for optimization of the production process and objective comparison of the existing options. This could greatly improve the current situation in which many producers focus on traditional production, discarding new production methods that take into account many more criteria because of the added complexity to operational and strategic management. Moreover, this methodology is adaptable to be improved in iterative versions and to be applied to new bio-economic models, which overcome the current limitations in the field. Therefore, it is beneficial to consider incorporating this type of analysis in future directions of research.

4.1 Implications for theory and practice

Throughout the theoretical approach here, two main aspects have been highlighted: 1) the need for both reliable data and objective indicators to prevent adverse environmental impact and 2) the importance of the integration of the main aspects of cleaner production with the economic efficiency of the company. In this regard, although the present work describes several indicators as objective as possible, the dependence on the quantity and quality of the available data has been reaffirmed as one of the main barriers when developing this type of methodology. This highlights the importance of developing new information technologies to be applied to aquaculture, starting with the development of a data lake or a data warehouse, which feeds all of the information gathered by the company as well as several external variables into the analysis, making it possible for the business to apply numerous data-dependent techniques to lead farms to be data driven enterprises.

In contrast, the increasing complexity involved in this integration causes most research studies to analyze only a few factors, disregarding others. Accordingly, the methodology developed in this study applies MCDM optimization techniques to the feeding selection strategy in aquaculture farms to allow the decision makers to integrate and prioritize different criteria, despite the subjectivity in the perception of their relative importance and the potential opposition to its results, allowing for the objective integration of variables and facilitation of decision making. This study represents a new step and a significant advance in the efficient management of aquaculture production and feeding strategies as well as in the academic analysis of the joint effects of many of these criteria.

In addition, one of the most striking research findings in terms of environmental sustainability is the lack of inclusion of contamination and waste indicators in organic labelling and production regulations and how it affects the results of these production practices. As the previous section has described, the feed that is marketed for organic production has this consideration because it comes from a sustainable fishery, but it is lacking in terms of efficiency in the use of fish or waste and pollutants generated per kg significantly worse than those of other alternatives. This suggests that within the aquaculture industry, what is an environmentally sustainable production is not properly defined, which confuses both producers and consumers. This finding is consistent with the conclusion reached by Madin and Macreadie (2015), who asserted that the inclusion of carbon footprints indicators could potentially have benefits for both the consumer and producer.

Finally, the application of the methodology to the culture of Gilthead seabream in sea cages and feeding decisions under three scenarios on decision-maker preferences shows that new ways of production that place value on other aspects of farming to reach profitability, such as quality or sustainability, imply that substantial changes in feeding decisions could be made. Furthermore, the sensitivity analysis conducted verifies that these decisions, based on the ranking of alternatives, are consistent, further emphasizing the importance of this analysis.

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References

Abdou, K., Aubin, J., Romdhane, M., Le Loc'h, F., & Lasram, F. (2017). Environmental assessment of seabass (Dicentrarchus labrax) and seabream (Sparus aurata) farming from a life cycle perspective: A case study of a Tunisian aquaculture farm. Aquaculture, 471, 204-212. doi: 10.1016/j.aquaculture.2017.01.019

Alasalvar, C., Shahidi, F., & Kazuo, M. (2011). Handbook of seafood quality, safety and health applications. Chichester, West Sussex, UK: Wiley-Blackwell.

Besson, M., Vandeputte, M., van Arendonk, J., Aubin, J., de Boer, I., Quillet, E., & Komen, H. (2016). Influence of water temperature on the economic value of growth rate in fish farming: The case of sea bass (Dicentrarchus labrax) cage farming in the Mediterranean. Aquaculture, 462, 47-55. doi: 10.1016/j.aquaculture.2016.04.030

Bourke, G., Stagnitti, F., & Mitchell, B. (1993). A decision support system for aquaculture research and management. Aquacultural Engineering, 12(2), 111-123. doi: 10.1016/0144-8609(93)90020-c

Boyd, C.E. (2015). Overview of aquaculture feeds: Global impacts of ingredient use. In: A. Davids (Eds.), Feed and Feeding Practices in Aquaculture. Woodhead Publishing Series in Food Science, Technology and Nutrition, 3-25.

Brett, J.R. (1979). Environmental factors and growth. Fish Physiology 8, 599–675. doi: 10.1016/S1546-5098(08)60033-3.

BOSTOCK, J. (2010). The application of science and technology development in shaping current and future aquaculture production systems. The Journal Of Agricultural Science, 149(S1), 133-141. doi: 10.1017/s0021859610001127

Cabral, J.B., Luczywo, N.A. & Zanazzi, J.L. (2016). Scikit-Criteria: Colección de Métodos de Análisis Multi-Criterio Integrado Al Stack Científico de Python. XLV Jornadas Argentinas de Informática E Investigación Operativa (45JAIIO)-XIV Simposio Argentino de Investigación Operativa (SIO), 59–66.

Vieira, L., & Amaral, F. (2016). Barriers and strategies applying Cleaner Production: a systematic review. Journal Of Cleaner Production, 113, 5-16. doi: 10.1016/j.jclepro.2015.11.034

Casini, M., Mocenni, C., Paoletti, S., & Pranzo, M. (2015). Decision support system development for integrated management of European coastal lagoons. Environmental Modelling & Software, 64, 47-57. doi: 10.1016/j.envsoft.2014.11.008

Chan, F., & Kumar, N. (2007). Global supplier development considering risk factors using fuzzy extended AHP-based approach. Omega, 35(4), 417-431. doi: 10.1016/j.omega.2005.08.004

Cobo, A., Llorente, I., & Luna, L. (2015). Swarm Intelligence in Optimal Management of Aquaculture Farms. In: Handbook of Operations Research in Agriculture and the Agri-Food Industry. Springer.

Cobo, Á., Llorente, I., Luna, L., & Luna, M. (2018). A decision support system for fish farming using particle swarm optimization. Computers And Electronics In Agriculture. doi: 10.1016/j.compag.2018.03.036

Conte, F. S., & Ahmadi, A. (2010). AQUARIUS: A decision support system for aquaculture. In ASABE - 21st Century Watershed Technology: Improving Water Quality and Environment (pp. 10-15)

Cordier, M., Brichon, G., Weber, J., & Zwingelstein, G. (2002). Changes in the fatty acid composition of phospholipids in tissues of farmed sea bass (Dicentrarchus labrax) during an annual cycle. Roles of environmental temperature and salinity. Comparative Biochemistry And Physiology Part B: Biochemistry And Molecular Biology, 133(3), 281-288. doi: 10.1016/s1096-4959(02)00149-5

Criste, V., Panaite, T. D., Banciu, A., Vasile, G., Criste, R. D. & Arama, M. (2016). Use of analytical hierarchy process based on production performance/cost/environmental impact, in evaluating the efficiency of compound feeds formulations for laying hens. Scientific Papers-Animal Science Series: Lucrări Ştiinţifice - Seria Zootehnie, 66, 141-147.

Cui, W., & Chui, T. (2017). Temporal variations in water quality in a brackish tidal pond: Implications for governing processes and management strategies. Journal Of Environmental Management, 193, 108-117. doi: 10.1016/j.jenvman.2017.01.073

Dapueto, G., Massa, F., Costa, S., Cimoli, L., Olivari, E., & Chiantore, M. et al. (2015). A spatial multi-criteria evaluation for site selection of offshore marine fish farm in the Ligurian Sea, Italy. Ocean & Coastal Management, 116, 64-77. doi: 10.1016/j.ocecoaman.2015.06.030

de Verdal, H., Komen, H., Quillet, E., Chatain, B., Allal, F., Benzie, J., & Vandeputte, M. (2017). Improving feed efficiency in fish using selective breeding: a review. Reviews In Aquaculture, 10(4), 833-851. doi: 10.1111/raq.12202

Denham, F., Howieson, J., Solah, V., & Biswas, W. (2015). Environmental supply chain management in the seafood industry: past, present and future approaches. Journal Of Cleaner Production, 90, 82-90. doi: 10.1016/j.jclepro.2014.11.079

Draganovic, V., Jørgensen, S., Boom, R., Jonkers, J., Riesen, G., & van der Goot, A. (2013). Sustainability assessment of salmonid feed using energy, classical exergy and eco-exergy analysis. Ecological Indicators, 34, 277-289. doi: 10.1016/j.ecolind.2013.05.017

Edwards, P. (2015). Aquaculture environment interactions: Past, present and likely future trends. Aquaculture, 447, 2-14. doi: 10.1016/j.aquaculture.2015.02.001

El-Gayar, O., & Leung, P. (2001). A multiple criteria decision making framework for regional aquaculture development. European Journal Of Operational Research, 133(3), 462-482. doi: 10.1016/s0377-2217(00)00183-1

Ernst, D., Bolte, J., & Nath, S. (2000). AquaFarm: simulation and decision support for aquaculture facility design and management planning. Aquacultural Engineering, 23(1-3), 121-179. doi: 10.1016/s0144-8609(00)00045-5

Estévez, R., & Gelcich, S. (2015). Participative multi-criteria decision analysis in marine management and conservation: Research progress and the challenge of integrating value judgments and uncertainty. Marine Policy, 61, 1-7. doi: 10.1016/j.marpol.2015.06.022

European Commission, 2008. Commission Regulation No 889/2008 of 5 September 2008 laying down detailed rules for the implementation of Council Regulation (EC) No 834/2007 on organic production and labelling of organic products with regard to organic production, labelling and control. Including amendments. http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1515078877100&uri=CELEX:02008R0889-20180101

Grigorakis, K. (2010). Effects of Nutrition and Aquaculture Practices on Fish Quality, in: Alasalvar, C., Shahidi, F., Miyashita, K., Wanasundara, U. (Eds.), Handbook of Seafood Quality, Safety and Health Applications. Wiley-Blackwell, 82-95.

Halide, H., Stigebrandt, A., Rehbein, M., & McKinnon, A. (2009). Developing a decision support system for sustainable cage aquaculture. Environmental Modelling & Software, 24(6), 694-702. doi: 10.1016/j.envsoft.2008.10.013

Hens, L., Block, C., Cabello-Eras, J., Sagastume-Gutierez, A., Garcia-Lorenzo, D., & Chamorro, C. et al. (2018). On the evolution of "Cleaner Production" as a concept and a practice. Journal Of Cleaner Production, 172, 3323-3333. doi: 10.1016/j.jclepro.2017.11.082

Hwang, C.L. & Yoon, K. (1981) Multiple Attribute Decision Making: Methods and Applications. Springer-Verlag, New York. http://dx.doi.org/10.1007/978-3-642-48318-9

Ivanco, M., Hou, G., & Michaeli, J. (2017). Sensitivity analysis method to address user disparities in the analytic hierarchy process. Expert Systems With Applications, 90, 111-126. doi: 10.1016/j.eswa.2017.08.003

Lembo, G., Jokumsen, A., Spedicato, M., Facchini, M., & Bitetto, I. (2018). Assessing stakeholder's experience and sensitivity on key issues for the economic growth of organic aquaculture production. Marine Policy, 87, 84-93. doi: 10.1016/j.marpol.2017.10.005

Llorente, I., & Luna, L. (2013). The Competitive Advantages Arising from Different Environmental Conditions in Seabream,Sparus aurata, Production in the Mediterranean Sea. Journal Of The World Aquaculture Society, 44(5), 611-627. doi: 10.1111/jwas.12069

Llorente, I., & Luna, L. (2014). Economic optimisation in seabream (Sparus aurata) aquaculture production using a particle swarm optimisation algorithm. Aquaculture International, 22(6), 1837-1849. doi: 10.1007/s10499-014-9786-2

Llorente, I., & Luna, L. (2015). Bioeconomic modelling in aquaculture: an overview of the literature. Aquaculture International, 24(4), 931-948. doi: 10.1007/s10499-015-9962-z

Luna, L. (2002). Economic analysis of finfish mariculture operations in Spain. Aquaculture Economics & Management, 6(1-2), 65-79. doi: 10.1080/13657300209380304

Madin, E., & Macreadie, P. (2015). Incorporating carbon footprints into seafood sustainability certification and eco-labels. Marine Policy, 57, 178-181. doi: 10.1016/j.marpol.2015.03.009

MAPAMA (2012). Estudio de la cadena de valor y formación de precios de la Dorada de acuicultura. Observatorio de Precios de los Alimentos, Madrid, Spain.

Mungkung, R., Aubin, J., Prihadi, T., Slembrouck, J., van der Werf, H., & Legendre, M. (2013). Life Cycle Assessment for environmentally sustainable aquaculture management: a case study of combined aquaculture systems for carp and tilapia. Journal Of Cleaner Production, 57, 249-256. doi: 10.1016/j.jclepro.2013.05.029

Pelletier, N., & Tyedmers, P. (2007). Feeding farmed salmon: Is organic better?. Aquaculture, 272(1-4), 399-416. doi: 10.1016/j.aquaculture.2007.06.024

Porter, M.E. & Kramer, M.R. (2006). Strategy and society: the link between competitive advantage and corporate social responsibility. Harvard Business Review 84, 78-92.

Rasmussen, R. (2001). Quality of farmed salmonids with emphasis on proximate composition, yield and sensory characteristics. Aquaculture Research, 32(10), 767-786. doi: 10.1046/j.1365-2109.2001.00617.x

Risius, A., Janssen, M., & Hamm, U. (2017). Consumer preferences for sustainable aquaculture products: Evidence from in-depth interviews, think aloud protocols and choice experiments. Appetite, 113, 246-254. doi: 10.1016/j.appet.2017.02.021

Saaty, R.W. (1987) The Analytic Hierarchy Process—What It Is and How It Is Used. Mathematical Modelling, 9, 161-176. http://dx.doi.org/10.1016/0270-0255(87)90473-8

Saaty, T.L. (1980). The Analytic Hierarchy Process. McGraw-Hill, New York

Samuel-Fitwi, B., Wuertz, S., Schroeder, J., & Schulz, C. (2012). Sustainability assessment tools to support aquaculture development. Journal Of Cleaner Production, 32, 183-192. doi: 10.1016/j.jclepro.2012.03.037

Shahidi, F. & Alasalvar, C. (2010). Marine Oils and Other Marine Nutraceuticals, in: Alasalvar, C., Shahidi, F., Miyashita, K., Wanasundara, U. (Eds.), Handbook of Seafood Quality, Safety and Health Applications. Wiley-Blackwell, 444–454.

Shih, Y. (2017). Integrated GIS and AHP for Marine Aquaculture Site Selection in Penghu Cove in Taiwan. Journal Of Coastal Zone Management, 20(1). doi: 10.4172/2473-3350.1000438

Stagnitti, F. (1997). A decision support tool for aquaculture. Environmental Modelling & Software, 12(2-3), 229-236. doi: 10.1016/s1364-8152(97)00015-7

Triantaphyllou, E., & Sánchez, A. (1997). A Sensitivity Analysis Approach for Some Deterministic Multi-Criteria Decision-Making Methods. Decision Sciences, 28(1), 151-194. doi: 10.1111/j.1540-5915.1997.tb01306.x

Wang, L., Chu, J., & Wu, J. (2007). Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process. International Journal Of Production Economics, 107(1), 151-163. doi: 10.1016/j.ijpe.2006.08.005

Zander, K., & Feucht, Y. (2017). Consumers’ Willingness to Pay for Sustainable Seafood Made in Europe. Journal Of International Food & Agribusiness Marketing, 30(3), 251-275. doi: 10.1080/08974438.2017.1413611

Zhang, H., Wei, Q., & Kang, M. (2014). Measurement of swimming pattern and body length of cultured Chinese sturgeon by use of imaging sonar. Aquaculture, 434, 184-187. doi: 10.1016/j.aquaculture.2014.08.024

Zhou, C., Lin, K., Xu, D., Chen, L., Guo, Q., Sun, C., & Yang, X. (2018). Near infrared computer vision and neuro-fuzzy model-based feeding decision system for fish in aquaculture. Computers And Electronics In Agriculture, 146, 114-124. doi: 10.1016/j.compag.2018.02.006