# UNIVERSIDAD DE CANTABRIA

PROGRAMA DE DOCTORADO EN CIENCIAS JURÍDICAS Y EMPRESARIALES

TESIS DOCTORAL

**Aplicaciones de ciencia de datos al proceso de toma de decisiones en la gestión de empresas de acuicultura.**

PHD THESIS

**Data science applications to the decision-making process in Aquaculture Business Management.**


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A mis padres

**“Si hoy sufrimos las decisiones de ayer, pensemos hoy en mañana”**

Julio Anguita

(21 Noviembre 1941 - 16 Mayo 2020)

La presente Tesis Doctoral se presenta en la modalidad de compendio de contribuciones científicas originales previamente publicadas o aceptadas en revistas científicas de impacto reconocido (JCR), siguiendo la normativa de la Universidad de Cantabria. Las referencias completas de los cuatro artículos que forman parte de esta tesis se detallan a continuación:

a. Luna, M., Llorente, I. & Cobo, A. (2019). Integration of environmental sustainability and product quality criteria in the decision-making process for feeding strategies in Seabream aquaculture companies. ***Journal of Cleaner Production*** 217, 691-701.

   https://doi.org/10.1016/j.jclepro.2019.01.248

   JCR impact factor 2018: 6.395 (Q1)

b. Luna, M., Llorente, I. & Cobo, A. (2019). Determination of feeding strategies in aquaculture farms using a multiple-criteria approach and genetic algorithms. ***Annals of Operations Research***.

   https://doi.org/10.1007/s10479-019-03227-w

   JCR impact factor 2018: 2.284 (Q2)

c. Luna, M., Llorente, I. & Cobo, A. (2020). Aquaculture production optimization in multi-cage farms subject to commercial and operational constraints. ***Biosystems Engineering***.

   JCR impact factor 2018: 2.983 (Q1)

d. Luna, M., Llorente, I. & Cobo, A. (Forthcoming 2020). A fuzzy approach to decision making in sea-cage aquaculture production. ***International Transactions in Operational Research***.

   JCR impact factor 2018: 2.341 (Q2)

The present Doctoral Thesis is presented as a compendium of original scientific contributions previously published or accepted in scientific journals of recognized impact (JCR), following the regulations of the University of Cantabria. The complete references of the four scientific papers that constitutes it are detailed below:

a. Luna, M., Llorente, I. & Cobo, A. (2019). Integration of environmental sustainability and product quality criteria in the decision-making process for feeding strategies in Seabream aquaculture companies. ***Journal of Cleaner Production*** 217, 691-701.

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# Presentación y síntesis del trabajo realizado

El continuo crecimiento de la demanda de productos marinos a lo largo del siglo XX ha propiciado el desarrollo no sostenible de la actividad pesquera que, con el tiempo, ha puesto en peligro la supervivencia de los recursos marinos. En este contexto, la acuicultura se ha convertido en la única alternativa para conseguir incrementar la oferta de pescado y dar respuesta a las demandas de los consumidores. Con este fin, la industria acuícola se ha apoyado a lo largo de las últimas décadas en los avances en I+D que han experimentado los campos de la biología y la tecnología, consiguiendo hacer viables nuevos métodos de producción más eficientes, como la producción intensiva, en distintas especies.

Sin embargo, en el caso de la producción de algunas especies, la industria ha entrado en su fase de madurez sin que la tendencia positiva en cuanto al crecimiento de la producción se haya visto acompañada por una disminución de la volatilidad de sus resultados, ni por un crecimiento de la eficiencia en la gestión de las empresas. Además, el nuevo contexto global de desarrollo de métodos de producción más complejos, cambios en los patrones de consumo de pescado e internacionalización del mercado ha generado una mayor competencia y nuevos riesgos y dificultades. Todo esto ha llevado a que algunas industrias, como la de producción de dorada y lubina, hayan evidenciado graves problemas económicos y de competitividad en los mercados.

En esta situación, la complejidad a la hora de abordar los procesos de toma de decisiones ha crecido exponencialmente, acrecentada por la necesidad de tomar decisiones en tiempo real analizando para ello grandes volúmenes de datos. Esto ha provocado que los sistemas tradicionales de gestión se hayan quedado obsoletos, a la espera de que la aplicación de Inteligencia Artificial y el Big Data puedan aportar soluciones. Así, tanto la comunidad científica como el sector coinciden hoy en día en la necesidad de aprovechar los avances de las nuevas tecnologías para lograr una mayor eficiencia en la gestión de empresas acuícolas.

Todas estas razones han motivado la realización de esta Tesis Doctoral cuyo objetivo es la aplicación de técnicas de análisis y procesamiento de datos (Tabla 1) para desarrollar nuevos modelos computacionales que aborden el proceso de toma de decisiones de las empresas de acuicultura, dando así una respuesta efectiva a los problemas mencionados anteriormente. Este objetivo ha sido abordado siguiendo un modelo de innovación incremental, que comienza con la determinación e integración de los criterios de decisión más importantes y avanza con el desarrollo secuencial de metodologías complejas apoyadas en técnicas de inteligencia artificial hasta conseguir la optimización de las principales decisiones estratégicas y operativas del sector.

Desde nuestro punto de vista, el desarrollo de estas metodologías no solo ha significado una novedad técnica respecto a los sistemas de ayuda a la toma de decisiones actuales, sino también un avance significativo en su eficacia en diferentes escenarios. En este sentido, la aplicación de técnicas multicriterio ha permitido, en primer lugar, considerar criterios diferentes, y muchas veces subjetivos, en el proceso de toma de decisiones en función de la importancia de cada uno de ellos para el productor. Esto ha permitido incorporar los cambios en la sensibilidad del mercado hacia otros factores, como la sostenibilidad o la calidad del producto, que complementan la tradicional racionalidad económica ligada a la maximización del beneficio. Así, se ha demostrado que no solo es posible incrementar la productividad y rentabilidad de las empresas, sino también reducir el consumo de algunos insumos y sus efectos negativos sin reducir su productividad.

Además, con el fin de acercar la investigación a las necesidades reales de las empresas del sector, se han aplicado diferentes técnicas de análisis de datos para el desarrollo de modelos de simulación y optimización cada vez más completos. En este sentido, estos modelos han incrementado el uso de información real y su capacidad de ser aplicados a un gran número de unidades productivas con un horizonte temporal más amplio. Esto ha permitido también abordar por primera vez problemas de los gestores como la introducción de restricciones comerciales o la consideración de la incertidumbre en torno a algunos factores, con el fin último de reducir el riesgo.

Por último, este trabajo también aborda uno de los puntos críticos en la generación de conocimiento, la transferencia y la explotación de los resultados de la investigación. En este sentido, en el marco del proyecto europeo MedAID se ha desarrollado una aplicación web abierta, AquiAID, en la que cualquier agente interesado del sector pueden hacer uso de estos avances a través de una interfaz simple.

| Técnicas multicriterio |
| --- |
| - Analytic Hierarchy Process (AHP) |
| - Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) |
| Técnicas de Soft computing |
| Computación bioinspirada - Optimización: |
| - Genetic Algorithms (GA) |
| - Particle Swarm Optimization (PSO) |
| Sistemas difusos |
| - Triangular Fuzzy Numbers |
| - Fuzzy pay-off method |
| - Fuzzy TOPSIS |
| Herramientas de desarrollo |
| - Bases de datos: MySQL |
| - Programación Open source: Python |

Tabla 1. Resumen de técnicas y herramientas utilizadas

# Abstract and Presentation

The continued growth in the demand for seafood products throughout the 20th century led the fishing sector to a scenario of wear and stagnation, in which a clear depletion of natural fish resources was observed. In this context, aquaculture production was conceived as an opportunity to increase the supply of fish and respond to consumer demands. In order to achieve this goal, the aquaculture industry has benefited from the R&D advances in the fields of biology and technology, making new and more efficient production methods, such as intensive production, viable for different species. These advancements were very beneficial for the aquaculture industry, which experienced the greatest growth in supply and demand in its history.

However, the industry has now entered into a phase of maturity and the positive trend in the production of certain species has not been matched by an equivalent decrease in the volatility of its results, nor by a growth in the efficiency of aquaculture companies' management. In addition, the global context of development of new production methods and market internationalization has led to increased competition across borders and has generated new risks and difficulties. This has resulted in some industries, such as the production of sea bream and sea bass, having to continuously deal with economic crises, affecting the competitiveness of the whole sector.

Due to this challenge, the complexity of the decision-making process and the need for real-time decisions based on large volumes of data have grown exponentially. The traditional management systems have become obsolete and the new decision support systems are facing more complex problems for they which require new techniques of Artificial Intelligence and Big Data. For these reasons, both the scientific community and the sector agree on the need to take advantage of the advances in new technologies to achieve a greater business management efficiency.

All these concerns have prompted the realization of this doctoral thesis, which aims to apply different data science techniques (Table 2) to develop new computational models that address the problems of the decision-making process of aquaculture companies. This objective has been addressed following a model of incremental innovation, which starts with the determination of the most important decision criteria in this new context and advances with the sequential development of complex methodologies supported by artificial intelligence techniques in order to optimize the main strategic and operational decisions.

From our point of view, the development of these methodologies has not only meant a technical novelty with respect to current decision support systems, but also a significant advance in the results of these in different scenarios. In this regard, the application of multi-criteria techniques has allowed us to consider different, and sometimes subjective, criteria in the decision-making process according to the producer’s priorities. This has made it possible to demonstrate, with their integration in different simulation and optimization models, that it is not only possible to increase the productivity and profitability of aquaculture companies, but also to reduce the consumption of some inputs and their negative effects on the environment without reducing the companies’ productivity, something which is very important to meeting the current consumers’ demands.

In addition, the application of data analysis techniques and the development of complex computational models has made it possible to address the most complex problems in the sector. In this way, some common behaviors in the sector have been modelled and confirmed, bringing these methodologies closer to the reality of the aquaculture companies. At the same time, the scope of these techniques has been generalized, applying these methods in larger companies, with multiple cages, like those that currently form the sector and with a long planning horizon, for multiple lots. Lastly, progress has been made in other aspects that were less developed until now, such as the introduction of commercial constraints or the consideration of the uncertainty regarding certain factors, with the aim of reducing risks and hazards.

Lastly, this work also addresses one of the critical points in the generation of knowledge, the transfer and exploitation of research results. In this regard, in the framework of the European project MedAID, an open web application has been developed, AquiAID (Artificial Intelligence Decisions in Aquaculture), in which any interested stakeholder can make use of these advances through a simple interface.

| Multi-criteria Techniques |
|---|
| - Analytic Hierarchy Process (AHP) |
| - Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) |
| Soft computing techniques |
| Bio-inspired computing: |
| - Genetic Algorithms (GA) |
| - Particle Swarm Optimization (PSO) |
| Fuzzy systems |
| - Triangular Fuzzy Numbers |
| - Fuzzy pay-off method |
| - Fuzzy TOPSIS |
| Software and development tools |
| - Databases: MySQL |
| - Open source programming: Python |

Table 2. Summary of techniques and tools

ÍNDICE

# Capítulo 1

# *Introducción*

## 1.1. Motivación

La innovación tecnológica está reconocida como el generador principal de crecimiento, siendo para las compañías una fuente primaria de ventajas competitivas sostenibles a largo plazo (Teece et al., 1997). En este sentido, la revolución tecnológica que se ha producido en las últimas décadas se considera una de las mayores de la historia, ya que ha cambiado de forma drástica las posibilidades de muchas empresas e, incluso, el mercado en su conjunto. Esta revolución se ha producido a un ritmo más elevado que nunca, no solo por la capacidad de desarrollo de nuevos productos o servicios, sino también por la reducción del tiempo de transmisión y penetración de esos avances en el mercado[1]. Además, junto con estos factores han aparecido otros factores aceleradores del cambio como, por ejemplo, una nueva actitud de los consumidores que han adoptado un papel más exigente en el proceso de compra, dejando de ser el tradicional sujeto pasivo para convertirse en un comprador que demanda nuevas características de los productos/servicios que consume (Voinea and Filip, 2011).

El gran alcance de estos cambios, apoyado por la facilidad de los consumidores para acceder a ellos gracias a internet y los smartphones ha revolucionado campos tan distintos como el comercio, la educación, la medicina o la gestión de las empresas. Más concretamente, los procesos de gestión y control de las empresas se han aprovechado en gran medida de los avances en las nuevas Tecnologías de la Información y la Comunicación (TICs), las cuales han posibilitado la realización de un gran número de procesos gracias a la reducción de costes y tiempo que suponen. Esto se debe principalmente a la mejora experimentada en la capacidad de gestión y análisis de grandes volúmenes de datos (Big Data) y al desarrollo de nuevas herramientas y modelos apoyados en la Inteligencia Artificial (IA).

Sin embargo, la innovación está también considerada como una fuente importante de riesgo, disrupción competitiva y desigualdades sociales y ambientales que, además, se ve afectada por factores externos imprevistos o incontrolables (Hall and Vredenburg, 2003). Asimismo, el gran alcance y velocidad de los avances tecnológicos realizados ha incrementado los retos que las empresas deben afrontar, obligándolas a actualizarse rápidamente para no ser desplazadas del mercado o incurrir en nuevos riesgos. De esta forma, la interacción de estos avances y el resto de factores influyentes en el mercado, los cuales se mantienen en continua evolución, ha provocado que, si se realiza un

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[1] Cuando se comparan en función del tiempo que han tardado en llegar a 50 millones de usuarios, se observan grandes diferencias entre las innovaciones clásicas, como el teléfono (50 años) o la televisión (22 años), y las aplicaciones desarrolladas en los últimos años, como *Instagram* (17 meses) o *Pokemon Go* (19 días). Fuente: www.statista.com/

análisis sectorial, sea posible detectar nuevos desafíos en todas las industrias. Esto provoca que el cambio de modelo productivo sea tan necesario como complejo y exija un análisis en detalle para cada empresa.

Otro de los principales retos a los que se enfrentan las empresas es, tal como se mencionaba anteriormente, la evolución de las expectativas de todos los agentes relacionados con la empresa (*stakeholders*). Entre ellos destacan los consumidores, quienes exigen cada vez más a los productores que atiendan sus demandas no solo en cuanto a la tradicional búsqueda del precio mínimo posible, sino también en términos de responsabilidad medioambiental o calidad del producto. De esta manera, las estrategias de innovación son cada vez más complejas, debiendo ser flexibles para adaptarse a las nuevas formas de producción, como las alternativas de producción más limpia, integrando los objetivos económicos tradicionales con nuevos objetivos para favorecer el uso eficiente de los recursos naturales (Vieira y Amaral, 2016).

En este sentido, los factores de cambio han repercutido especialmente en el sector primario debido al impacto directo que tienen sus actividades en los recursos naturales y, en el caso de la industria agroalimentaria, en la alimentación y salud de los consumidores. El sector acuícola no es una excepción puesto que, a lo largo de los últimos años, las empresas de acuicultura han experimentado una transformación tecnológica en los sistemas de producción que abarca desde el cambio hacia sistemas de producción intensiva, hasta la mejora del control de la producción gracias al uso de sensores inteligentes y al llamado *internet de las cosas* (IoT). Además, se ha producido un gran número de cambios significativos en los patrones de consumo de sus clientes, que priorizan las opciones más sostenibles y saludables. Todo ello, bajo la atenta mirada de unas instituciones reguladoras cada día más concienciadas con la responsabilidad social de las empresas.

Como consecuencia, la complejidad de los procesos de gestión y toma de decisiones de las empresas de acuicultura ha aumentado exponencialmente. Así, las empresas deben considerar un número cada vez mayor de factores influyentes en su actividad, ya sean biológicos, económicos o medioambientales. Además, la consideración de horizontes temporales más largos ha significado un aumento de la incertidumbre en torno a la evolución de dichos factores. Todo esto ha llevado a un aumento considerable del volumen de datos a tener en cuenta, el cual ya se encuentra fuera de los límites de la capacidad humana, que requiere del uso de las nuevas tecnologías para obtenerlos, almacenarlos y procesarlos adecuadamente. De esta forma, las empresas de acuicultura demandan, cada vez más, el desarrollo de sistemas de ayuda a la toma de decisiones que apoyen a los gestores tanto en los procesos de gestión operativa en tiempo real, como en la planificación estratégica a largo plazo.

Con el objetivo de responder a dicho aumento de la complejidad de la gestión acuícola, la implementación de las nuevas tecnologías en la acuicultura es un reto para los investigadores, que plantean modelos de mayor complejidad con el objetivo de conseguir adaptar sus utilidades lo más posible a la realidad, así como para las empresas que, a raíz de la presión competitiva del mercado, se ven obligadas a dar una respuesta efectiva a todos estos cambios. En este sentido, cabe preguntarse cuál sería la capacidad de respuesta de una empresa acuícola tradicional si irrumpe en el mercado una nueva empresa que incorpore todas las posibilidades que ofrecen las nuevas tecnologías. Si se tienen en cuenta las ventajas competitivas que estas tecnologías proporcionan parece evidente que su incorporación no es una opción sino una necesidad cuando se busca mantener la capacidad de creación de valor de la empresa y su supervivencia a largo plazo.

La necesidad de responder a los retos a los que se enfrenta la acuicultura de forma conjunta dificulta la realización de trabajos que aborden el problema desde un único campo de conocimiento. Dado que el resultado de la actividad se ve afectado por múltiples factores, su gestión demanda un enfoque multidisciplinar (Llorente and Luna, 2012). Esto ha llevado a la comunidad científica a la realización de trabajos de investigación conjuntos, entre los que cabe destacar el trabajo de biólogos, economistas e ingenieros en el desarrollo de modelos bioeconómicos, herramientas de gestión y sistemas de ayuda a la toma de decisiones (DSS) para mejorar la eficiencia y competitividad de las empresas del sector.

Tradicionalmente, la mayoría de estos modelos se han basado en la experiencia acumulada en la pesca y otras actividades del sector primario, como la agricultura o la silvicultura, para aumentar la eficiencia y la rentabilidad de la acuicultura a escala industrial (Bjørndal et al. 2004). Sin embargo, como se detallará en apartados posteriores, existen en la actualidad diversos estudios aplicados específicamente a la acuicultura cuyo objetivo es el desarrollo de modelos bio-econométricos, como se recoge en diversos trabajos de revisión (Llorente y Luna, 2016; Peñalosa Martinell et al., 2019), o de sistemas de optimización y apoyo a las principales decisiones estratégicas y operativas de las empresas, como es la decisión de la localización de la granja (Dapueto et al., 2015) o la evaluación de la capacidad de producción (Hermawan, 2015).

En ese contexto, la ausencia de modelos que permitiesen optimizar el proceso de toma de decisiones estratégicas y operativas sirvió como punto de inicio de la línea de trabajo del grupo IDES en la cual se inscribe esta tesis. En su primera fase, los directores de esta tesis, el Dr. Ángel Cobo Ortega y el Dr. Ignacio Llorente García, desarrollaron un primer modelo que permitía optimizar el resultado económico de una única unidad jaula a partir de un modelo bioeconómico (basado en las funciones de crecimiento, alimentación y mortalidad) que se apoyaba en una metaheurística de búsqueda de las estrategias de cultivo más cercanas al óptimo.

El trabajo realizado fue novedoso en cuanto a la aplicación de estas técnicas de investigación en el sector acuícola y su línea de trabajo despertó el interés de la comunidad científica y la industria, como muestra su inclusión como uno de los puntos principales del proyecto europeo H2020, MedAID. De esta forma, constituye un punto de partida muy interesante para la aplicación de las nuevas Tecnologías de la Información y la Comunicación al desarrollo de todo tipo de técnicas que permitan abordar el proceso de toma de decisiones. Sin embargo, como parte de ese trabajo, ya se señalaron una serie de líneas futuras de investigación que, aunque en ese momento no se llevaron a cabo debido a su complejidad técnica, mejorarían la utilidad de las herramientas de apoyo a la toma de decisiones en los procesos de producción acuícola, incrementando la eficiencia de los mismos y la competitividad de las empresas.

La presente Tesis Doctoral tiene por objetivo realizar una aportación significativa en el desarrollo de esta línea de investigación, superando los cuellos de botella señalados en los trabajos anteriores y las nuevas barreras a las que se enfrenta en la actualidad la gestión de empresas de acuicultura:

a. En primer lugar, de forma análoga a lo que ocurre en otras industrias, una de las necesidades más demandadas por un gran número de agentes del sector de la acuicultura es un cambio de paradigma, abandonando la consideración de un único objetivo de maximización del beneficio para adoptar estrategias de innovación cuyo objetivo sea el desarrollo sostenible. Sin embargo, hasta el momento, la mayoría de los trabajos realizados tratan de optimizar el resultado económico de la empresa, dejando de lado aspectos de gran importancia como la eficiencia en el uso de recursos, la calidad del producto o la reducción de los efectos negativos de las acciones realizadas sobre el medio ambiente.

b. Además, hasta el momento, la limitación de capacidad técnica y computacional para abordar el problema de forma completa ha provocado que las metodologías actuales consideren la existencia de una sola jaula o jaulas idénticas, lo que supone que todas actúan igual, es decir, inician su actividad (siembra) y la finalizan (despesque) en el mismo momento y con idéntico resultado. Este supuesto ha permitido simplificar el cálculo, pero no refleja la realidad de las empresas del sector. En el mismo sentido, la evolución del sector acuícola ha favorecido la concentración empresarial, por lo que cada vez las empresas tienen un mayor número de jaulas cuya planificación debe ser realizada con un horizonte temporal más amplio, haciendo necesaria la consideración de las interrelaciones entre los distintos lotes producidos por la empresa. Por estas razones, también se debe valorar la posibilidad de combinar diversas formas de producción en una misma empresa con el fin de cumplir los objetivos marcados por el productor para responder a la demanda del mercado.

c. Por otro lado, los nuevos sistemas de apoyo a la toma de decisiones deben tratar de dejar atrás los modelos deterministas tradicionalmente utilizados, los cuales no tienen en cuenta la gran variabilidad e incertidumbre en torno a algunos factores. En este sentido, es importante considerar los diferentes escenarios posibles, así como la posibilidad de ser flexible ante cambios inesperados variando en tiempo real la estrategia, lo que requiere una forma de toma decisiones dinámica, frente al restrictivo enfoque estático de la mayor parte de los trabajos.

d. Por último, la ausencia de sistemas que incorporen la necesidad de considerar las restricciones operativas (limitando el volumen despescado en un momento dado a causa de limitaciones laborales o físicas) y comerciales (fijando una cantidad mínima o máxima a comercializar en un periodo de tiempo) que condicionan las principales decisiones estratégicas y operativas, es uno de los factores que condicionan la aplicación de estos a la realidad de la gestión de empresas acuícolas.

Todo esto implica un aumento exponencial del número de decisiones tomadas, de la cantidad de posibles estrategias evaluadas y, por supuesto, de la complejidad de los modelos desarrollados para ello. Sin embargo, los avances en las TICs y, principalmente, en el análisis de datos a través de las técnicas de Inteligencia artificial y el incremento en la capacidad y velocidad de computación, nos permiten hoy en día el desarrollo de metodologías que superan estas limitaciones.

En conclusión, la elección de esta línea de investigación tiene como motivación la necesidad de nuevas metodologías de apoyo a la toma de decisiones en una actividad, la acuicultura, que, debido a la interacción de factores económicos, medioambientales y biológicos, es especialmente compleja. Esto requiere la aplicación de técnicas de gestión novedosas que permita superar las limitaciones de los trabajos realizados hasta la fecha, con el fin último de ser implementadas en los sistemas de gestión de empresas del sector. Esta innovación requiere un enfoque multidisciplinar, aunando conocimientos biológicos, relacionados con la cría de la especie, con técnicas de economía y matemáticas para la modelización de sistemas de producción, además de conocimientos técnicos para su implementación en sistemas operativos y de apoyo a la toma de decisiones.

Además, el fin último de esta línea de investigación debe ser la transmisión del conocimiento generado a la práctica de sector acuícola. Para ello es necesario el desarrollo de sistemas de ayuda a la toma de decisiones que se aprovechen de los avances en las nuevas tecnologías para facilitar la accesibilidad y usabilidad de técnicas complejas a usuario que no tengan necesariamente conocimientos sobre las técnicas o el software empleado.

En este sentido, la realización de esta tesis en el marco del proyecto europeo H2020" MedAID" en el que participa el grupo de investigación IDES-UC de la Universidad de Cantabria, es uno de los factores que más fomentan la vocación eminentemente práctica de esta Tesis Doctoral, siendo una prioridad contribuir a la reducción de la distancia entre el ámbito académico y las empresas.

## 1.2. Objetivos de la investigación

A partir de las necesidades de investigación que motivan esta tesis se ha definido el siguiente objetivo principal:

*El estudio del proceso de toma de decisiones en las empresas de acuicultura y el desarrollo de modelos computacionales y técnicas de análisis de datos que permitan mejorar las herramientas de apoyo a dichos procesos con el fin último de dar una respuesta efectiva a la necesidad de mejoras en la eficiencia productiva y la competitividad empresarial en un contexto de creciente complejidad e incertidumbre debido a la evolución de los factores económicos, biológicos y medioambientales. Este objetivo se inscribe en una línea de trabajo incremental donde se plantean modelos y metodologías cada vez más adaptados a la realidad de las empresas del sector.*

Con esta finalidad, el trabajo realizado se ha estructurado en siete objetivos específicos que serán abordados a lo largo de los siguientes capítulos:

1. Estudiar la situación actual de las empresas del sector acuícola, los problemas de mayor importancia a los que se enfrentan y las alternativas de las que disponen.

2. Identificar los principales criterios influyentes en el proceso de toma de decisiones en acuicultura y las necesidades de datos, incluyendo las posibles fuentes de información, tanto cuando se consideran fines puramente económicos, como cuando se plantean nuevas formas de producción como, por ejemplo, la producción sostenible.

3. Determinar el método más adecuado para integrar dichos criterios en una única función objetivo que permita cuantificar el efecto de las distintas estrategias de producción sobre los resultados de la empresa y pueda ser utilizada como objetivo de optimización.

4. Desarrollar una metodología que permita optimizar las decisiones de alimentación, las cuales son consideradas las decisiones más complejas e influyentes en los resultados de la empresa. Por esta razón, se analizan de forma aislada, sin tener en cuenta otras decisiones, para una única unidad productiva y un solo lote.

5. Abordar la optimización del proceso de toma de decisiones de forma completa, es decir, integrando las principales decisiones como parte de un proceso conjunto a largo plazo que considere múltiples unidades de producción (jaulas) y lotes, manteniendo el enfoque de objetivo multicriterio.

6. Evaluar los efectos de la inclusión de restricciones complejas propias del negocio, ya sean operativas o comerciales, en el proceso de toma de decisiones; tanto desde el punto de vista de la eficiencia computacional de las metodologías desarrolladas, como de la utilidad y resultados de la decisión finalmente tomada.

7. Valorar la utilización de modelos computacionales que permitan considerar la incertidumbre e imprecisión respecto a la evolución de algunos factores, dejando atrás los modelos deterministas tradicionales.

Todos estos objetivos incluyen un enfoque práctico, que tiene por objetivo la transferencia del conocimiento a las empresas del sector. Esto queda patente, en primer lugar, con la utilización de datos reales en el proceso de prueba y calibración de todas las metodologías desarrollas y, finalmente, con el desarrollo de una aplicación web de ayuda a la toma de decisiones en el marco del proyecto europeo H2020 MedAID, en el cual participan más de 30 empresas, instituciones y grupos de investigación relacionados con el sector acuícola.

## 1.3. Estructura de la Tesis Doctoral

Con el fin de presentar de la forma más clara posible el trabajo realizado para alcanzar los objetivos principales, este se ha estructurado en los siguientes capítulos:

En este primer capítulo se sintetiza, a modo de introducción, la investigación preliminar realizada y el punto de partida del trabajo, los cuales serán desarrollados con posterioridad en las aportaciones de esta Tesis Doctoral. Para ello, se comienza describiendo las razones que han motivado su realización, la finalidad del trabajo de investigación llevado a cabo y la estructura de este documento. A continuación, se explica, de forma resumida, el estado de la cuestión en el sector acuícola, tanto en lo que se refiere a la descripción de los problemas a los que se enfrentan los empresarios del sector, como a al desarrollo de soluciones a dichos problemas gracias a las posibilidades que ofrecen las nuevas tecnologías. Por lo tanto, este primer capítulo describe de manera resumida los hallazgos generales obtenidos como parte del primer objetivo planteado en esta Tesis Doctoral, los cuales se desarrollan más detalladamente, en la medida en que se emplean de forma específica, en los siguientes capítulos.

En el Capítulo 2, que se corresponde con el primero de los artículos publicados (Tabla 1), titulado "*Integration of environmental sustainability and product quality criteria in the decision-making process for feeding strategies in Seabream aquaculture companies*", se identifican las principales variables de decisión en acuicultura y se desarrolla un modelo que permite la integración de múltiples factores en el proceso de toma de decisiones, teniendo en cuenta las preferencias de los gestores. Para ello se realizan tres agrupaciones de criterios (económicos, medioambientales y de calidad del producto) y se presentan los factores más importantes de cada uno en función de las diferentes formas de producción existentes en acuicultura, ya analizadas en diversos artículos y trabajos previos. Después, se propone una metodología que permite valorar la importancia de cada uno de dichos criterios de decisión en función de las preferencias de cada productor para integrarlos en una única función objetivo. Para terminar el capítulo, se comprueba con datos reales cómo esa función objetivo puede ser utilizada en el proceso de selección del pienso entre un número finito de propuestas, optimizando así los resultados en una hipotética granja de acuicultura de dorada. Este capítulo da respuesta a los objetivos específicos 2 y 3.

El Capítulo 3, titulado "*Determination of feeding strategies in aquaculture farms using a multiple-criteria approach and genetic algorithms*", se corresponde con el segundo de los artículos publicados (tabla 1). En este caso, se desarrolla una metodología que permite, mediante la utilización de la función objetivo multicriterio del capítulo anterior y una técnica de computación evolutiva, en concreto Algoritmos Genéticos (GA), abordar una de las decisiones más complejas y determinantes en acuicultura, la estrategia de alimentación. Esta decisión presenta un problema añadido a lo ya descrito, y es que, aunque tradicionalmente se trataba de una única selección de pienso entre un número de opciones disponibles en el mercado, en la actualidad se lleva a cabo una decisión dinámica formada por un conjunto de decisiones individuales (semanales o mensuales). Así, este proceso dinámico permite adaptar la estrategia a las condiciones ambientales con la secuenciación del uso de diferentes alternativas de alimentación. Para cumplir con este objetivo, se ha utilizado un GA, un método adaptativo de Inteligencia Artificial (IA), que permite llevar a cabo este proceso de optimización, evolucionando desde una alternativa inicial aleatoria hasta encontrar una estrategia que combine las decisiones de forma óptima. Además, se ha probado su capacidad en dos escenarios de preferencias de los productores para encontrar una alternativa mejor a las disponibles actualmente, manteniendo un coste computacional (tiempo) bajo. En este capítulo se da respuesta al objetivo específico número 4 y permite que esta metodología sea integrada en herramientas o sistemas más complejos que analicen también otras decisiones.

El Capítulo 4, titulado "*Aquaculture production optimization in multi-cage farms subject to commercial and operational constraints*", contiene la investigación recogida en el tercero de los artículos que forman parte de esta Tesis Doctoral (Tabla 1). Dicho artículo tiene como fin abordar los objetivos específicos 5 y 6, es decir, continuar avanzando en la optimización del proceso de decisión hasta diseñar una metodología completa de ayuda a la toma de decisiones de producción. Para ello, se ha desarrollado una metodología que permite optimizar las principales decisiones de producción en acuicultura (fecha de siembra, especie y peso de los alevines utilizados, estrategia de alimentación y fecha de despesque) en contextos complejos en los que se dispone de más de una jaula (*multijaula*), un horizonte temporal de varios años (*multilote*) y varias alternativas de alimentación y selección de los alevines. Además, se ha considerado también la posible existencia de restricciones operativas y comerciales que puedan limitar la producción o fijar algunos valores. Como prueba de su utilidad, se ha simulado y discutido el funcionamiento de esta metodología tanto desde el punto de vista de la validez de los resultados obtenidos, como desde el de su desempeño computacional, es decir, su eficiencia y capacidad a la hora de encontrar soluciones óptimas. Esto constituye una aplicación novedosa en acuicultura que no solo aborda el problema en la situación más compleja computacionalmente, dado el gran número de soluciones posibles, si no que propone y analiza la inclusión de restricciones, lo que acerca el problema a la realidad de la gestión de las empresas del sector.

El capítulo 5 recoge los avances realizados en el último de los artículos de investigación incluidos en esta tesis, llamado "*A fuzzy approach to decision making in sea-cage aquaculture production*", y aborda el séptimo objetivo específico de la misma. En este capítulo se proponen dos metodologías que permiten avanzar desde los modelos deterministas tradicionales, a un modelo que considera la incertidumbre de algunos de los factores exógenos influyentes en la actividad. Con este objetivo, no solo se tiene en cuenta el escenario esperado en el que se desarrollará cada estrategia de producción, sino también dos escenarios extremos en los cuales dichos factores evolucionarían de forma positiva o negativa para el productor. Para ellos se han aplicado metodologías de números difusos que permiten estimar el valor actual a cada una de esas estrategias. De esta forma, se trata de dar respuesta a la incertidumbre existente en el sector acuícola mediante la consideración de la volatilidad de algunos factores para incluir la relación riesgo-beneficio en la toma de decisiones. Los resultados obtenidos han mostrado la idoneidad de su aplicación en el sector acuícola, recomendando la selección de alternativas menos beneficiosas en algunos escenarios, pero con un riesgo significativamente menor, algo que es coherente con los conocimientos de teoría económica y de decisión ampliamente comprobados en otros sectores.

El capítulo 6 presenta una aplicación web, desarrollada dentro del marco del proyecto europeo MedAID, con el fin de permitir a los productores comprobar de primera mano las nuevas posibilidades que las tecnologías de la información y la comunicación pueden aportar a este sector y, además, realizar la planificación estratégica de cada una de sus unidades productivas introduciendo los datos reales de su empresa. En este sentido, la aplicación desarrollada incentiva a la introducción de datos reales ya que no solo personaliza los resultados al caso concreto de cada productor, sino que se retroalimenta de ellos para mejorar las metodologías aplicadas a través de técnicas de análisis de datos.  Está aplicación es de acceso libre a todos los usuarios por lo que se presenta una breve explicación de su funcionamiento y resultados para, a continuación, indicar la forma de acceso a la misma para que pueda ser utilizada.

Por último, en los capítulos 7, con la discusión de los resultados y conclusión, y 8, futuras líneas de investigación, se presentan los principales hallazgos que nos ha permitido alcanzar la realización de esta Tesis Doctoral. En cuanto a estos resultados y conclusiones, es posible destacar que, desde nuestro punto de vista, no son solo de interés para la comunidad científica y la industria, sino también para otros stakeholders como los reguladores u otras instituciones relacionadas con el sector. Por último, se apunta a algunas de las líneas de investigación que se infieren de este trabajo y en las que se continúa trabajando de forma ininterrumpida.

| Publicación | Impacto JCR 2018 | Categorías SCI y SSCI |
|---|---|---|
| Luna, M., Llorente, I., & Cobo, Á. (2019). Integration of environmental sustainability and product quality criteria in the decision-making process for feeding strategies in seabream aquaculture companies. **Journal of cleaner production**, 217, 691-701. | 6.395 | Green & Sustainable Science & Technology (6/35)<br>Engineering, Environmental (8/52)<br>Environmental Sciences (18/250) |
| Luna, M., Llorente, I., & Cobo, Á. (2019). Determination of feeding strategies in aquaculture farms using a multiple-criteria approach and genetic algorithms. **Annals of Operations Research.** | 2.284 | Operations Research & Management Science (30/84) |
| Luna, M., Llorente, I., & Cobo, Á. (2020). Aquaculture production optimization in multi-cage farms subject to commercial and operational constraints. **Biosystems Engineering.** | 2.983 | Agriculture Multidisciplinary (7/56)<br>Agricultural Engineering (4/13) |
| Luna, M., Llorente, I., & Cobo, Á. (2020). A fuzzy approach to decision making in sea-cage aquaculture production. **International Transactions in Operational Research** | 2.341 | Operations Research & Management Science (29/84) |

Tabla 1. Relación de publicaciones científicas incluidas como compendio en la presente Tesis Doctoral.

## 1.4. Los procesos de toma de decisiones en acuicultura

### 1.4.1. El problema de la gestión de empresas acuícolas

Tradicionalmente, la acuicultura marina se ha llevado a cabo de forma mayoritaria en lagunas y estanques costeros mediante el uso de sistemas de producción extensiva. Estos sistemas de producción eran considerados como la opción menos arriesgada, ya que mantenían la densidad de población en niveles controlables y presentaban resultados aceptables en las principales variables biológicas como el crecimiento o la mortalidad. Sin embargo, el cambio en los patrones de producción y consumo forzaron a las empresas a avanzar en la búsqueda de una mayor productividad, para hacer frente a la demanda creciente; rentabilidad, que permita nuevas inversiones; y eficiencia, para conseguir una oferta competitiva que responda a las exigencias del mercado. Por esta razón, de la misma forma que en otras industrias del sector primario, las empresas de acuicultura se han apoyado en los avances tecnológicos para evolucionar hacia métodos más productivos, como la producción intensiva.

Por lo que se refiere a la pesca, principal sustitutivo de la acuicultura, la oferta comenzó a resentirse del crecimiento exponencial e incontrolado que había experimentado durante la segunda mitad del siglo XX, el cual puso en riesgo la sostenibilidad de las poblaciones de peces. Eso desembocó en una difícil situación para la pesca, en la cual tanto las posibilidades de pesca como el endurecimiento de la regulación pesquera provocaron un estancamiento de la oferta de pescado salvaje. Desde la perspectiva de la acuicultura, esto significó un estímulo al desarrollo de la industria que, junto con la aparición de nuevas innovaciones tecnológicas, llevó al sector a una posición relevante en todo el mundo y a un crecimiento continuo que se mantiene hoy en día.

En ese contexto, el mercado de pescado ha continuado creciendo y expandiéndose impulsado por el aumento en la demanda que, gracias al crecimiento exponencial de la acuicultura (Fig. 1), pudo ser atendida a pesar del citado descenso de las posibilidades de pesca (FAO, 2010), lo que supone uno de los mayores hitos del sector hasta el momento. Específicamente, dentro del sector acuícola, la forma de producción que ha tenido mayor importancia en el mercado durante este tiempo ha sido la cría intensiva en jaulas marinas (STEFC, 2019), ya que presenta una gran ventaja comparativa y competitiva a nivel mundial: la reducción de costes operativos, sin necesidad de energía para el bombeo, la aireación o el tratamiento del agua, por su emplazamiento en el mar.

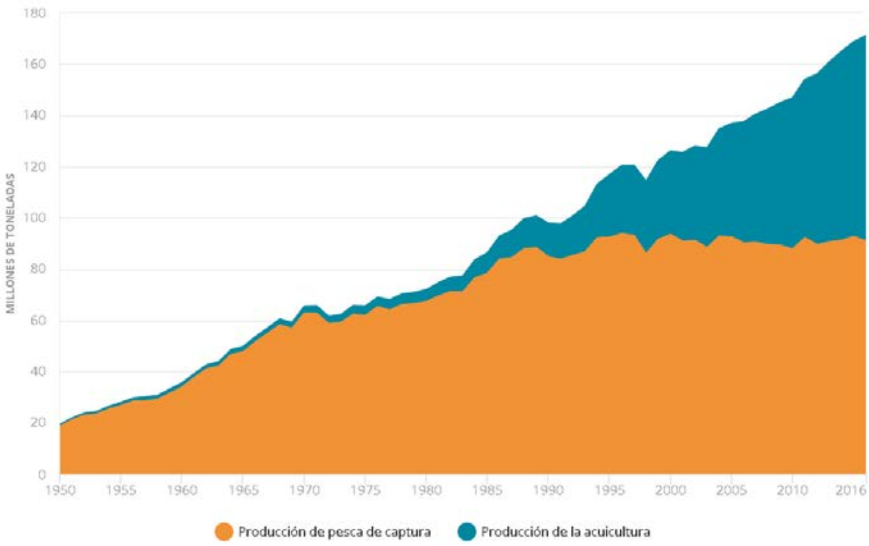


Fig. 1 - Evolución de la producción de pescado (Fuente: FAO, 2010)

Todas estas razones podrían llevar a creer que la acuicultura es una inversión con poco riesgo y alta rentabilidad. Sin embargo, el sector acuícola ha experimentado una gran volatilidad en los resultados de sus empresas a lo largo de los años con un crecimiento desigual, frecuentes crisis empresariales, y problemas que han requerido apoyo y regulación institucional. Esto se ha traducido en el sufrimiento de fuertes crisis, buen ejemplo de ello son las de la dorada y la lubina en la Unión Europea entre los años 2001 y 2002 (GascaLeyva et al., 2003) o la del salmón en Chile en el año 2007 (Mardones et al., 2009).

En el caso concreto que nos ocupa, la gestión del proceso de engorde de dorada en jaulas marinas, a pesar de que la inversión pública y privada en investigación para la mejora de la tecnología de cultivo ha logrado mejoras en los últimos años, estas han sido inferiores a las esperadas. A diferencia de lo ocurrido en la producción de Salmon en los años 90, la eficiencia técnica y la productividad no han experimentado mejoras significativas y la demanda no ha aumentado. De esta forma, en un contexto de incremento de la oferta y reducción de la demanda en algunos periodos, lo que conlleva una reducción de los precios de venta, y de aumento del coste de las materias primas, los márgenes empresariales se han reducido (Guillen et al., 2019). La principal respuesta de las empresas de dorada y lubina fue iniciar un proceso de concentración empresarial que permitió la obtención de economías de escala (Llorente et al., 2020) y la mejora de los indicadores de rendimiento económico. Sin embargo, todavía existe campo de mejora para la eficiencia en la gestión de la producción en dorada y lubina.

En cuanto a la mejora de la competitividad de la industria, se han utilizado dos vías principales. Por un lado, la expansión de la demanda, ya sea vía aumento en los mercados actuales (diferenciación por calidad, procesado etc.), o vía acceso a nuevos mercados. Por el otro, la reducción del coste medio de producción, aumentando así la eficiencia y el margen operativo. Este último aspecto es clave para las empresas de países como España o Italia, que cada vez más tienen que competir con productores de terceros países como Egipto, Túnez o Turquía que tienen ventajas competitivas en términos de costes de producción (como la mano de obra), administrativos o medioambientales (regulación menos exigente que la comunitaria). Sin embargo, el acceso a nuevos mercados no está siendo una tarea sencilla y la mejora de la eficiencia técnica ha visto fuertemente condicionada por los procesos productivos y la evolución de los factores, internos y externos, que les afectan.

Por lo tanto, entre los problemas que han llevado a muchas empresas a esa situación es posible destacar los siguientes:

a. Complejidad de las decisiones de producción.

Desde la perspectiva de las decisiones de producción, una de las razones que explican los problemas en la gestión de empresas de acuicultura es el gran número de decisiones complejas que deben ser tomadas y la cantidad de variables a tener en cuenta durante este proceso. Como se ha explicado en el primer apartado de esta tesis, de forma similar a otras industrias del sector primario, la gestión de las granjas de acuicultura se ha vuelto cada vez más compleja ya que se ve afectada por la interacción de un creciente número de factores, tanto internos como externos a la empresa, ya sean biológicos, económicos, medioambientales o tecnológicos. Este problema ha sido analizado en diversos estudios, como en el realizado por Llorente y Luna (2012).

En el caso de los factores externos, éstos son de gran importancia desde la primera fase cuando se produce la siembra de los alevines en las jaulas, debido a que el riesgo de provocar una pérdida del stock está en su punto máximo. Este proceso de siembra se puede realizar desde que los alevines pesan 15 gramos por lo que los factores externos que tienen más importancia son los biológicos y medioambientales, relativos a la sanidad, la temperatura y calidad del agua, así como aspectos genéticos, dado que los peces se encuentran en el momento de mayor debilidad. Hay que tener en cuenta que hay un cierto grado de incertidumbre en cuanto a estos factores, lo que dificulta la planificación de este proceso.

A partir de ese momento, durante un periodo de entre uno y dos años, se lleva a cabo el proceso de engorde con el objetivo principal de alcanzar el tamaño comercial (superior a 300 g) en el menor tiempo posible. La duración exacta del proceso de engorde depende de factores externos, biológicos y medioambientales, pero también de aspectos internos de la gestión de la empresa, tanto estratégicos como operativos. En este sentido, destaca la estrategia de alimentación ya que es una de las decisiones con más incidencia en el coste total de la empresa y con mayor influencia en el crecimiento de los peces y, por lo tanto, en los ingresos futuros. Además, otros criterios más alejados de lo económico, como los criterios medioambientales o de calidad del producto, también dependen en gran medida de la calidad del alimento utilizado. Por estas razones, la alimentación en acuicultura ha sido uno de los pilares de investigación e innovación, llevadas a cabo en la mayoría de casos por los fabricantes de pienso, centrados en la búsqueda de una formulación óptima que les permita tener una ventaja competitiva. Por último, cabe destacar que el proceso de selección de pienso realizado por el productor no siempre es el mismo y, mientras que en algunos casos es una decisión para todo el proceso, en otros es una estrategia dinámica más flexible que va variando semanal o mensualmente en función de las condiciones medioambientales y de mercado; ello implica una mayor dificultad para los programas de gestión o ayuda a la toma de decisiones.

En cuanto a la última fase del proceso, la fase de despesque, esta está condicionada por factores económicos, comerciales y operativos. En este punto, se ha de tomar la decisión sobre el momento y la forma en la que se vaciará cada jaula. De esta manera, los productores se enfrentan a restricciones operativas, ya que tienen limitaciones laborales o físicas en cuanto a la cantidad máxima de despesque, y comerciales, ante la necesidad de responder a los compromisos contractuales que fijan de forma anticipada la cantidad y el peso mínimo de venta en un momento fijo del año.

En conclusión, la explicación acerca del gran número de empresas que sufren una volatilidad muy alta de sus resultados puede estar en la dificultad que supone para los gestores la adopción de decisiones efectivas en una actividad donde interaccionan factores tan distintos como los económicos, los tecnológicos, biológicos y los medioambientales (Luna, 2002). Cabe destacar como una parte de las empresas de cría de algunas especies, dirigidas por gestores no profesionales, no suelen sobrevivir a los primeros años de gestión, poniendo de manifiesto la necesidad de una gestión eficaz.

b. Desajustes del Mercado Acuícola

La evolución del mercado en acuicultura ha sido otro de los retos a los que se han tenido que enfrentar muchos productores, provocando en algunos casos grandes pérdidas para sus empresas. Como se ha explicado, los avances tecnológicos han mejorado las posibilidades y la eficiencia del sector, pero al mismo tiempo ha aumentado la competitividad en el mercado.

En términos generales, la estrategia seguida para competir en el mercado ha sido la reducción de costes tratando de conseguir beneficios sostenibles para la empresa mediante una estrategia competitiva de liderazgo en precios. Este tipo de actuación, dada la reducción del margen comercial que implica, supone una gran dificultad para los productores y genera una situación en la que los aspectos tecnológicos de la empresa y el proceso de toma de decisiones cobran vital importancia.

Por otro lado, la globalización de la oferta, con la entrada de nuevos oferentes debida a la mayor apertura de los mercados internacionales y la difusión de las tecnologías de producción, ha situado a los países desarrollados en una situación competitiva compleja frente a los países en vías de desarrollo, donde los costes son significativamente inferiores.

Todas estas razones han llevado a la búsqueda de nuevas vías para contrarrestar estos desajustes, provocando en unos casos la deslocalización de la producción y, en otros, obligando a las empresas localizadas en países desarrollados a buscar una ventaja en la innovación tecnológica y la diferenciación por calidad y sostenibilidad de la oferta.

c. Dificultad para ofertar productos diferenciados de forma competitiva.

Una vez analizada la complejidad de las decisiones de producción, que dificulta la gestión eficiente de la empresa, junto a la situación del mercado, que provoca una reducción de los márgenes debida a la alta competencia, algunas empresas han tratado de buscar alternativas a las formas de producción y venta tradicionales. La principal alternativa ha sido realizar una estrategia de diferenciación a través de la obtención de sellos de calidad o de etiquetado ecológico que les permita competir en el mercado en un momento en el que las exigencias de los consumidores en estos sentidos están aumentando. Esto constituye una oportunidad para producir pescado que, según el estudio realizado por Zander y Feucht (2018), los consumidores estarían dispuestos a pagar entre un 7% y un 20% por encima del precio del de acuicultura tradicional, dependiendo del país de origen y de algunos atributos del producto.

No obstante, los productores a veces perciben algunos riesgos en estas formas de producción como resultado de los precios más altos de alimentos orgánicos y sostenibles o de la mayor incertidumbre en términos de regulación y precios de venta, lo que hace que el número de granjas que aplican estas nuevas formas de producción sea más bajo de lo esperado. A este respecto, varios estudios, como el realizado por Bostock (2010), han identificado la necesidad de más impulsos políticos para asumir costes externos realistas y promover un cambio real en la acuicultura hacia la producción sostenible.

Con el objetivo de reducir esa incertidumbre, existe un gran número de sellos y etiquetas ecológicas oficiales creadas en un principio para unificar y simplificar este proceso. Sin embargo, éstas han generado un gran número de problemas para los productores. Por un lado, es posible encontrar grandes diferencias entre los criterios de las diferentes certificaciones y, aunque algunas etiquetas ecológicas sí presentan un impacto en las decisiones de compra, las ventajas que aportan esos productos ecológicos no están bien reconocidas y los clientes no confían en ellos (Risius et al., 2017), lo que va en contra del objetivo inicial de simplificación del proceso. Por otro lado, la certificación de productos orgánicos por parte de un tercero confiable ha resultado en un coste muy alto para los productores. El Reglamento nº 889/2008 de la Comisión Europea, de 5 de septiembre de 2008, y sus diversas enmiendas, han establecido normas específicas que, en algunas ocasiones, terminan por suponer un coste superior al beneficio añadido de esta forma de producción.

Sin embargo, la diferenciación del producto exige también un mayor control sobre la producción, reforzando la necesidad de innovación en las tecnologías de gestión que permita mejorar la eficiencia y limitar el diferencial de precio que han de pagar los consumidores.

### 1.4.2. Tecnologías de la información aplicadas a la toma de decisiones

La disponibilidad de soluciones tecnológicas que ayuden en el proceso de toma de decisiones de las empresas depende en gran medida de la complejidad del problema a abordar y de los medios de los que se dispongan. En el caso de la acuicultura, a pesar de que se trata de un sector con problemas de gestión, no es fácil encontrar un gran número de trabajos que aborden estos procesos (Mathisen et al., 2016). Esto se debe en gran medida a que el avance de los sistemas de control y ayuda a la toma de decisiones se ha visto retrasado por dichos factores, dado que nos encontramos en una industria muy compleja que, durante muchos años, no ha dispuesto de los medios suficientes para hacer grandes inversiones en I+D+i.

Sin embargo, esta situación se ha ido revirtiendo poco a poco a lo largo de los últimos años, lo que ha llevado a avances significativos en muchos ámbitos. Por un lado, hay un gran número de investigadores trabajando para dar respuesta a los problemas del sector, muchos de ellos abordando los problemas concretos de cada industria, algo sobre lo que se hará hincapié en el análisis del estado de la cuestión de cada una de las aportaciones de esta Tesis Doctoral. Pero, a su vez, los empresarios del sector están cada vez más interesados en llevar dichos avances a la práctica, llevados por el convencimiento de que la mejor forma de incrementar la competitividad de la empresa es a través de tecnología y la implementación de innovaciones en el proceso de cría. Esto nos permite hablar de una tendencia generalizada en el sector, que se hace más intensa en las especies que se encuentran en un ciclo de producción más avanzado.

Por estas razones, el desarrollo de sistemas expertos de gestión y sistemas de ayuda a la toma de decisiones (DSS por sus siglas en inglés) en acuicultura ha crecido, aunque lentamente, en los últimos años, tratando de dar respuesta a las necesidades de los productores en un contexto de incremento exponencial del número de variables y el volumen de datos a tener en cuenta. De esta forma, este tipo de sistemas son cada vez más necesarios a la hora de abordar las decisiones complejas de las principales compañías, ya sean operativas o estratégicas. Hoy en día, podemos encontrar sistemas para la gestión sostenible de la producción de moluscos (Conte and Ahmadi, 2010), de la producción de langostino (Yu and Leung, 2007 y 2010), para las decisiones de elección del lugar y la capacidad máxima de producción de pescado en jaulas marinas (Halide et al., 2009) o, como ya hemos citado anteriormente, el desarrollado por Cobo et al. (2019) para la gestión de la producción de dorada y lubina.

Estas herramientas tienen como fin último permitir el uso de metodologías complejas de forma sencilla por parte de los usuarios finales, sin exigir unos conocimientos técnicos elevados, como apoyo a los procesos de gestión y planificación. De esta forma, el empleo de los avances en Big Data e Inteligencia Artificial ha permitido mejorar la capacidad de las empresas acuícolas para la toma de decisiones y el desarrollo sistemas de control (Zhou et al., 2018). Para llegar a ello, si se analizan en detalle estos sistemas, es posible sintetizar los esfuerzos de investigación realizados en este ámbito en dos líneas de trabajo principales:

a. Modelos de simulación

Los modelos de simulación son muy útiles, tanto para entender el funcionamiento de los sistemas de producción, como para realizar predicciones sobre su desempeño a lo largo del periodo de producción. En el caso de las actividades económicas que dependen del comportamiento de sistemas biológicos, como la acuicultura, han surgido los llamados modelos bioeconómicos que permiten dar respuesta matemáticamente a la necesidad de integrar factores económicos, biológicos, técnicos y ambientales para el estudio de los procesos de producción y así incrementar su eficiencia y productividad (Allen et al., 1984). En un primer momento, estos modelos consideraban variables económicas como el precio y el coste, aunque con el paso del tiempo se van añadiendo otras como la medición del riesgo, la capacidad máxima de producción o la estimación del impacto de diversas contingencias como, por ejemplo, los cambios en la legislación correspondiente.

Sin embargo, la existencia de un gran número de factores hace que la tarea de modelar y predecir la evolución de la producción sea especialmente difícil, más aún si se tienen en cuenta la falta de datos de calidad y los problemas específicos del sector, como se explica en el apartado anterior. Por esta razón, los primeros modelos replicaban lo realizado en otras actividades más avanzadas en este ámbito como la ganadería, la agricultura o, por supuesto, la pesca, con el objetivo de mejorar la eficiencia y rentabilidad de la actividad acuícola a una escala industrial (Bjørndal et al. 2004). Así, se iniciaron diferentes líneas de investigación con el objetivo de modelar las particularidades de cada especie como, por ejemplo, en el cultivo de camarones (Karp et al., 1986; Leung y Shang, 1989), en el caso del salmón (Bjørndal, 1988; Arnason, 1992; Heaps, 1993; Heaps, 1995; Mistiaen y Strand, 1998) o en la producción de dorada y lubina (Llorente y Luna, 2013; 2014). Para más tarde abordar nuevos objetivos, llegar a nuevas especies y ser parte de cada vez más metodologías de optimización, como se muestra en el trabajo de revisión de Llorente and Luna (2015).

b. Técnicas de optimización:

A partir de la existencia de los primeros modelos de simulación, se comenzó a desarrollar metodologías para la búsqueda de alternativas que optimicen los resultados de cada decisión. Para ello es necesario fijar la función objetivo a maximizar o minimizar junto a las variables sobre las que el decisor puede actuar; por lo que la introducción de cada vez más factores y variables en los modelos de simulación es esencial para la mejora de estas técnicas.

En el sector acuícola existe un gran número de decisiones estratégicas y operativas que pueden ser modeladas matemáticamente para buscar su óptimo, siendo su complejidad la que marca el tipo de técnica a utilizar y la dificultad para desarrollarla. Desde el inicio de la aplicación de estas técnicas de optimización a los procesos de toma de decisiones de producción, los modelos se centraron en determinar las fechas de despesque que maximizan el valor de la producción (Asche y Bjørndal, 2011). En el caso de la gestión óptima de la producción de dorada y lubina, los primeros avances se publicaron a finales de los años 90 como, por ejemplo, el estudio de desarrollado por Rizzo y Spagnolo (1996) que analizaba el efecto de algunas variables operativas en el resultado económico final, identificando las estrategias que lo llevaban a su punto máximo. Pero hubo que esperar hasta el siglo XXI para el desarrollo de esta línea de investigación con trabajos realizados con diversos objetivos como minimizar los costes operativos (León et al., 2001), maximizar los beneficios a través de las fechas de siembra y despesque (Gasca-Leyva et al., 2002; León et al., 2006; Hernández et al. 2007) o la planificación de la producción de lotes consecutivos (Cobo et al, 2015).

Sin embargo, todavía existe una gran necesidad de nuevos modelos de optimización que permitan a los productores ir más allá de los modelos tradicionales, basados en los efectos de la temperatura del agua o la ración de alimentación (Seginer, 2016), y plantear nuevos modelos y objetivos de producción que cada vez son más demandados como, por ejemplo, la sostenibilidad ambiental. A este respecto, Rabassó y Hernández (2015) fueron pioneros en la aplicación de un modelo bioeconómico para evaluar el impacto ambiental de la producción de dorada en jaulas en el mar. Todavía se dispone de pocos estudios que consideran estos objetivos de forma conjunta con los anteriores, como los estudios de Dapueto et al. (2015) o Shih (2017) que los aplican a la selección de la localización, y un gran número de trabajos de revisión que destacan su necesidad en el sector, desde el desarrollado por Mardle y Pascoe (1999), hasta el publicado por Mathisen et al. (2016).

## 1.5. Aportaciones del trabajo realizado a los modelos de gestión actuales.

El proceso de gestión de empresas de acuicultura se ve constantemente afectado por la interacción de un gran número de factores, tanto externos como internos, y comprende un elevado número de procesos de toma de decisiones diferentes, los cuales presentan sus propias características y dificultades. Tradicionalmente, las decisiones operativas más importantes en las empresas de acuicultura marina se han agrupado en 4 aspectos principales: la fecha de siembra, los alevines utilizados, el pienso utilizado para su alimentación y la fecha de despesque. En consecuencia, los principales modelos de gestión en el sector se han centrado en la búsqueda de las decisiones, para cada uno de esos aspectos, que maximizan el beneficio económico obtenido. Además, como se explicaba en el apartado 1.1, esta búsqueda se realizaba para una única unidad productiva o jaula y un solo lote de pescado, tratando de simplificar el problema (Fig. 2).


Fig. 2 – Representación de los sistemas de gestión tradicionales

Sin embargo, a pesar de que estas decisiones continúan, a día de hoy, representando los aspectos más importantes a la hora de optimizar la estrategia de producción en acuicultura, la aplicación en la práctica de sistemas de gestión basados en el esquema anterior ha presentado diversas limitaciones a la hora de adaptarse a las necesidades actuales de los productores. Esto se debe a los cambios ocurridos en el sector que han provocado la aparición de nuevos aspectos a tener en cuenta, pero también a que los modelos anteriores, si bien abarcan las principales decisiones de engorde, no consideraban la actividad de una granja en su conjunto. Por esta razón, el trabajo presentado ha tratado de dar una respuesta efectiva a estas limitaciones a través del desarrollo de una metodología que permita mejorar los modelos de gestión actuales.

Este desarrollo se ha abordado en una línea de trabajo incremental donde se plantean modelos y metodologías cada vez más complejos y adaptados a la realidad de las empresas del sector, que no solo constituyen una novedad en la aplicación científica de las nuevas Tecnologías de la Información y la Comunicación en acuicultura, sino también una aportación práctica y aplicable a los sistemas de apoyo a la toma de decisiones de los productores aplicados actualmente en la acuicultura, aspecto en el que nos centramos en este apartado.

En la primera etapa, se ha desarrollado una metodología que permite adaptar el objetivo de producción a los importantes cambios producidos en el sector, teniendo en cuenta nuevos criterios como la perspectiva de los consumidores a la hora de valorar el producto final o los criterios que buscan hacer de la producción acuícola una producción sostenible a largo plazo económica y medioambientalmente (regulación). La incorporación de nuevos criterios de decisión requiere el uso de una nueva función objetivo multicriterio (capítulo 2), que puede ser utilizada como objetivo de producción en distintas aplicaciones o sistemas expertos para dar entrada a las nuevas formas de producción en los modelos de gestión actuales (Fig. 3).


Fig. 3 – Primer etapa: Avance hacia el uso de funciones objetivo multicriterio

En la segunda etapa, se ha tratado de superar los modelos tradicionales que parten de la hipótesis de que solo se utiliza un pienso a lo largo del proceso de engorde, descartando la posibilidad de realizar cambios en esta decisión, lo que constituye una limitación a la hora de optimizar la estrategia de alimentación. Como se ha comprobado empíricamente en los últimos años, la secuenciación de diversos piensos a lo largo del año, dependiendo de factores internos y externos como la temperatura del agua o la estacionalidad del mercado, permite a las empresas de acuicultura obtener mejores resultados. La estrategia de alimentación se ha abordado de forma individual tanto por la complejidad de la decisión cuando se permite la secuenciación de distintos piensos, como por la importancia de una decisión, que tiene un efecto directo muy alto sobre todos los criterios considerados en acuicultura. Para abordar este problema se ha desarrollado una metodología (capítulo 3) que se apoya en el uso de Algoritmos Genéticos para encontrar la combinación de piensos que maximiza los resultados de la empresa, manteniendo el punto de vista multicriterio (Fig. 4).


Fig. 4 – Segunda etapa: Introducción de estrategias de alimentación dinámicas.

La tercera etapa aborda la limitación que aleja en mayor medida a los modelos tradicionales de su aplicación práctica en las empresas del sector, la consideración de una única unidad de producción y un lote que se siembra y despesca completamente en un momento del tiempo. Esto difiere cada vez más de la realidad de las empresas de acuicultura debido a que estas tienen cada vez mayor tamaño, realizan la planificación de múltiples unidades a la vez, ya sean jaulas o tanques, y con un horizonte temporal cada vez más largo en el que se van sucediendo distintos momentos de siembra y despesque. Por esta razón, se ha desarrollado una metodología (capítulo 4) que permite optimizar las decisiones de producción de varias especies (multiespecie) a largo plazo (multilote) para un gran número de jaulas (multijaula), manteniendo la consideración de múltiples piensos y objetivos (Fig. 5). Esta fase constituye una mejora de la capacidad de gestión de los productores acuícolas y la comprensión del desempeño de las principales variables de la granja de forma conjunta.


Fig. 5 – Tercera etapa: Optimización de las decisiones de producción.

En la cuarta y última etapa, los modelos de simulación y optimización desarrollados han sido tradicionalmente deterministas. De esta forma, no tienen en cuenta la incertidumbre real que existe en torno a los diferentes factores biológicos, técnicos, económicos o ambientales que conducen a una alta variabilidad de los resultados obtenidos en situaciones teóricamente similares. Esto constituye una limitación no solo cuando se aplican en la práctica, sino también para considerar ciertos criterios, como el riesgo operativo de algunas decisiones, en los modelos de toma de decisiones. Con respecto a esta incertidumbre, aunque a corto plazo es más fácil estimar, con una alta probabilidad, el valor de algunos de los factores que influyen en los procesos de la acuicultura y sus desviaciones, existen situaciones que dificultan en gran medida esa consideración, debiendo considerar posibles escenarios.

En este contexto, la última aportación de trabajo de investigación llevado a cabo en esta tesis ha sido el desarrollo de una metodología de toma de decisiones en acuicultura que tiene en cuenta la incertidumbre de algunas variables, como el crecimiento de los peces, ayudando a los productores a considerar el riesgo asociado a cada alternativa cuando enfrentar decisiones fundamentales.


Fig. 6. Consideración de la incertidumbre en torno a los principales factores influyentes en los resultados de las empresas.

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# Capítulo 2

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

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# 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;

***List of abbreviations and notations:***

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| CP | Cleaner Production |
| DSS | Decision Support System |
| MCDM | Multiple-Criteria Decision-Making |
| TOPSIS | Technique of Order Preference by Similarity to Ideal Solution |
| $d^+(X)$ | Separation of criteria values of *X* from the positive ideal solutions. |
| $d^-(X)$ | Separation of criteria values of *X* from the negative ideal solutions. |

## Resumen en español

El rápido crecimiento de la producción acuícola a lo largo de los últimos años ha permitido responder a la creciente demanda mundial de pescado en un contexto de estancamiento de la producción pesquera. Este crecimiento ha sido generado gracias a los procesos de innovación llevados a cabo para transformar un sector formado por empresas tradicionales en la industria acuícola actual, con grandes empresas y métodos de producción avanzados. Sin embargo, las empresas del sector también se han enfrentado a nuevos desafíos, como la sostenibilidad medioambiental o el incremento de la calidad del producto.

Hoy en día, la industria ha alcanzado una fase de mayor madurez en la que los gestores, conscientes de los efectos de la producción acuícola en su entorno, se enfrentan a un difícil marco regulatorio y a unos mercados globales muy exigentes, formados por empresas más competitivas y nuevos patrones de consumo. Todo ello, unido a la mayor escala de las empresas, ha provocado que las decisiones de gestión se hayan vuelto cada vez más complejas y, por lo tanto, ha alentado las demandas de los productores de sistemas de gestión y ayuda a la toma de decisiones que den respuesta a sus nuevas necesidades.

Por estas razones, el presente artículo tiene como objetivo la determinación de los criterios de decisión más importantes para los productores acuícolas, así como el desarrollo de una metodología multicriterio que permita integrarlos en una única función objetivo aplicable en diversos métodos de optimización.

### Metodología

A fin de alcanzar dicho objetivo, se ha llevado a cabo un proceso de desarrollo de metodología en fases. En primer lugar, a partir de un proceso de revisión de la literatura científica publicada hasta el momento y de las principales regulaciones que afectan al sector, se han identificado 9 criterios de decisión claves para el desarrollo de la producción acuícola, correspondientes a los objetivos económicos, de sostenibilidad medioambiental y de calidad del producto.

En segundo lugar, se han utilizado dos técnicas de toma de decisiones multicriterio (MCDM) para permitir a los gestores de empresas acuícolas la evaluación de la idoneidad de diferentes estrategias de producción en función de dichos criterios. De esta forma, se han aplicado la técnica AHP, con el objetivo de estimar la importancia que el productor otorga a cada criterio a partir de evaluaciones por pares, y la técnica TOPSIS para abordar la complejidad que supone tomar decisiones fundamentadas en criterios diferentes y, a veces, opuestos entre sí. Esto ha permitido integrar el grado de cumplimiento de cada criterio en función de su importancia en una sola valoración que representa la distancia de cada alternativa a una hipotética estrategia ideal, para en función de ese valor seleccionar al final del proceso la estrategia más cercana.

En este sentido, la metodología desarrollada no solo permite evaluar las estrategias de producción en función de múltiples criterios, sino que adapta el proceso de selección de la estrategia óptima a las preferencias de cada productor.

Resultados

La metodología desarrollada se ha aplicado a un problema de selección del pienso óptimo usando los datos de una granja de dorada en el Mediterráneo. Para ello se han planteado 3 escenarios de decisión, con diferentes preferencias de los productores, y se ha analizado la elección de pienso recomendada en cada uno de ellos.

Los resultados obtenidos han mostrado la utilidad de esta metodología para integrar numerosos criterios en la evaluación de diversas alternativas y para llevar a cabo un análisis que ponga a prueba el impacto de las diferentes estrategias en los resultados de las empresas. En este sentido, uno de los resultados principales de la integración de criterios económicos, medioambientales y de calidad en la función objetivo de las empresas es la confirmación de la posibilidad de incorporar los cambios en la sensibilidad del mercado hacia estos nuevos factores, como complemento, y no sustituto, de la tradicional racionalidad económica ligada a la maximización del beneficio.

## 2.1. 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 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 (Samuel-Fitwi et al., 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 multiple-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.

## 2.2. 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).

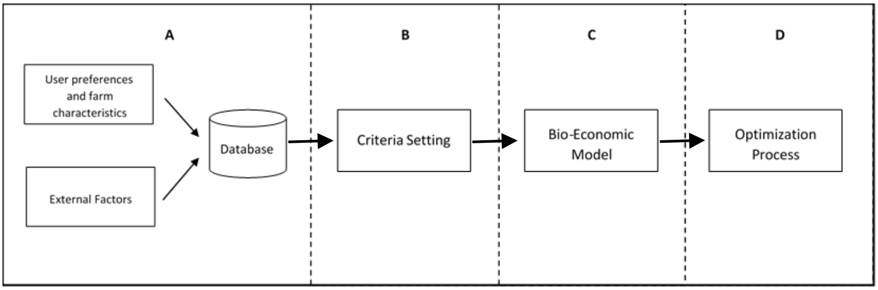


Fig 1. Software architecture according to the methodological approach.

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.

### 2.2.1. 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:

#### 2.2.1.1 Technical data of the farm and its cages.

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.

#### 2.2.1.2 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

#### 2.2.1.3 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.

#### 2.2.1.4 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.

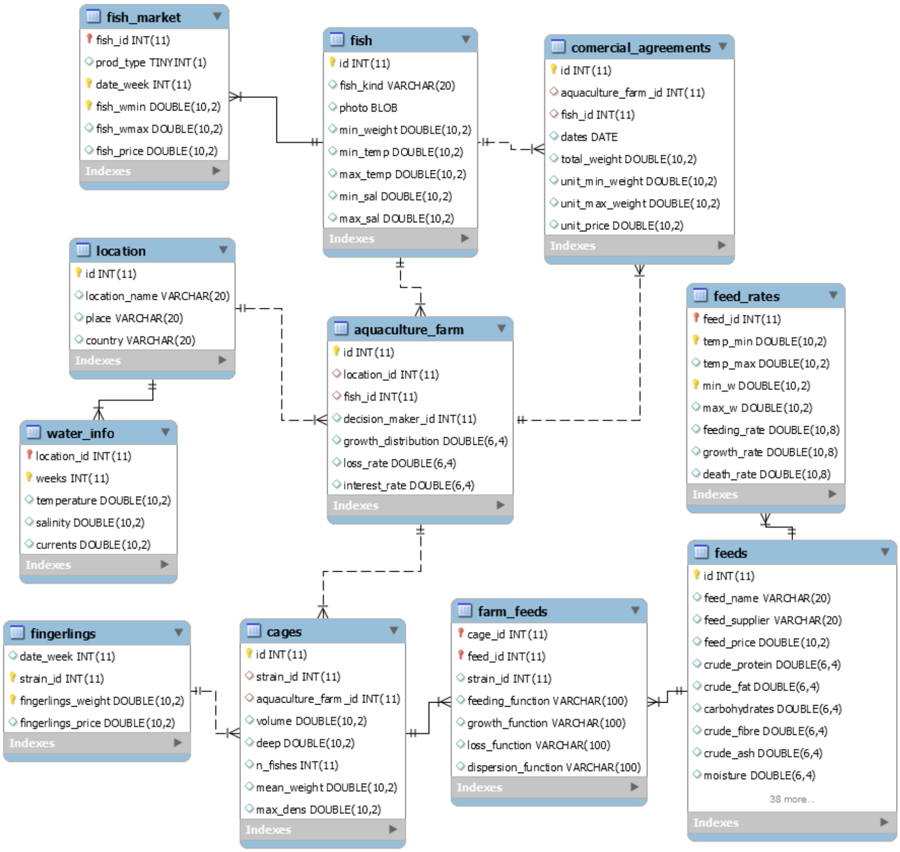


Fig 2. Entity-relationship model

### 2.2.2. 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.

#### 2.2.2.1 Economic criteria

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.

2.2.2.2 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 the amount of fish based feed needed to produce a unit weight of the cultured species (Fish-in Fish-out ratio), 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.

#### 2.2.2.3 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.

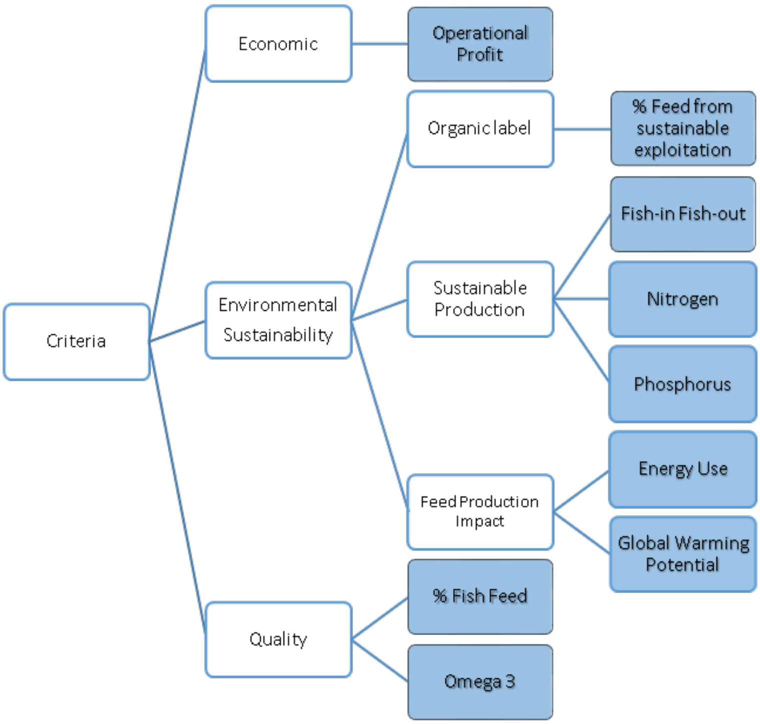


Fig. 3 Criteria hierarchy – tree structure: Highlighted boxes correspond to finally included criteria

### 2.2.3. 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.

### 2.2.4. 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.

2.2.4.1 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 (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.

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

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

### 2.2.4.2 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 (2), which is defined as the relative closeness to the ideal solution:

$$F(X) = \frac{d^-(X)}{d^-(X) + d^+(X)} \quad (2)$$

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.

## 2.3. 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.

### 2.3.1 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, 2002). 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

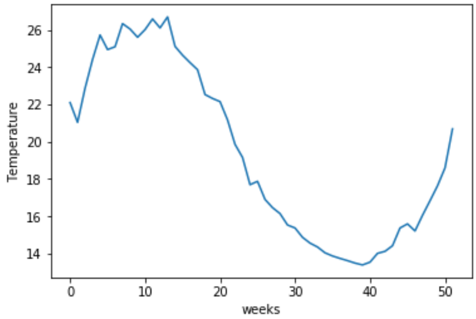


Fig. 4: Avg Temperature - Port Buoy 2720

### 2.3.2 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

### 2.3.3 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.

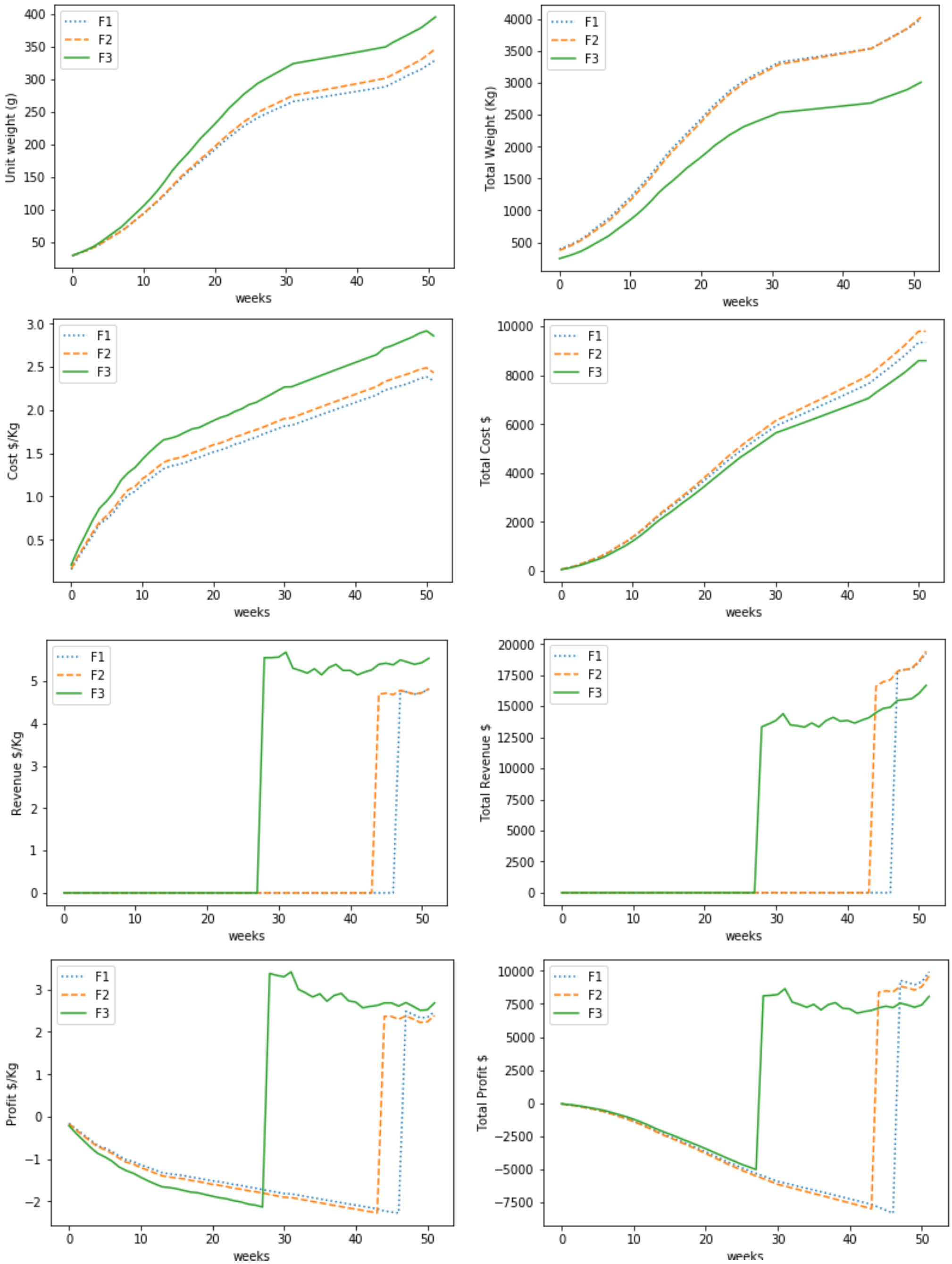


Fig. 5: Farm Evolution

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 |
| FCRtotal (%) | 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.

### 2.3.4 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.

### 2.3.5 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).

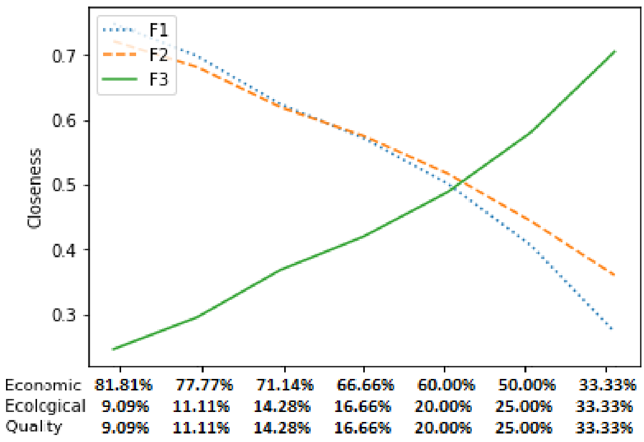


Fig. 6: Sensitivity analysis

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.

## 2.4. 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.

### 2.4.1 Implication 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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# Capítulo 3

## *Determination of feeding strategies in aquaculture farms using a multiple-criteria approach and genetic algorithms*

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# Determination of feeding strategies in aquaculture farms using a multiple-criteria approach and genetic algorithms

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## Abstract:

Since the 1990s, fishing production has stagnated and aquaculture has experienced an exponential growth thanks to the production on an industrial scale. One of the major challenges facing aquaculture companies is the management of breeding activity affected by biological, technical, environmental and economic factors. In recent years, decision-making has also become increasingly complex due to the need for managers to consider aspects other than economic ones, such as product quality or environmental sustainability. In this context, there is an increasing need for expert systems applied to decision-making processes that maximize the economic efficiency of the operational process. One of the production planning decisions more affected by these changes is the feeding strategy. The selection of the feed determines the growth of the fish, but also generates the greatest impact of the activity on the environment and determines the quality of the product. In addition, feed is the main production cost in finfish aquaculture. In order to address all these problems, the present work integrates a multiple-criteria methodology with a genetic algorithm that allows determining the best sequence of feeds to be used throughout the fattening period, depending on multiple optimization objectives. Results show its utility to generate and evaluate different alternatives and fulfill the initial hypothesis, demonstrating that the combination of several feeds at precise times may improve the results obtained by one-feed strategies.



## Keywords:

Aquaculture management; operational research; genetic algorithms; multiple-criteria; decision-making; feeding strategies;

## Resumen en español

A lo largo de las últimas décadas, el sector acuícola ha sido el sector de producción animal de más rápido crecimiento, en gran parte gracias a las innovaciones tecnológicas. Esto ha llevado a la acuicultura a ser una industria relevante en todo el mundo, pero, al mismo tiempo, también ha acrecentado algunos de los problemas de gestión sufridos por las empresas, lo que ha generado una gran volatilidad en sus resultados. Entre ellos destaca la dificultad de gestionar la producción a gran escala de una actividad fuertemente afectada por un gran número factores económicos, biológicos y medioambientales, cuyos objetivos deben dejar atrás el enfoque únicamente económico.

En este sentido, algunas decisiones no han sido abordadas adecuadamente debido a su gran complejidad, por lo que todavía se realizan en función de la experiencia de los productores. Entre ellas destaca la estrategia de alimentación, debido a la gran dificultad que supone la elección de piensos, que no se limita a una única elección del pienso más adecuado, sino que está formada por un conjunto de decisiones individuales que permiten adaptar la alimentación a las condiciones de cada momento. Además, esta es a la vez una de las decisiones con mayor impacto económico, ya que supone el mayor porcentaje de los costes, y una de las más afectadas por los cambios en el sector acuícola, ya que es el mayor condicionante del efecto medioambiental y en la calidad del producto.

Para abordar dicho problema, este artículo presenta una metodología de optimización, usando Algoritmos Genéticos, que permite determinar la estrategia de alimentación optima en base a la función multicriterio previamente desarrollada (capítulo 2).

<u>Metodología</u>

Cuando nos referimos al proceso de optimización de la estrategia de alimentación en acuicultura, entendemos que éste es un problema de optimización combinatoria, en el cual el productor dispone de un número finito de piensos y su objetivo es seleccionar cual debe ser usado en cada uno de los días/semanas/meses del proceso de producción {F1, F2…, Fm}. Por esta razón, se ha desarrollado una metodología específica basada en algoritmos genéticos que permite generar y evaluar diferentes estrategias alternativas, con un tiempo de computación razonable, como parte de un proceso evolutivo hasta llegar a una estrategia próxima al óptimo.

Con este fin, la metodología desarrollada también integra el uso de un modelo bioeconomico, que emplea las tasas de alimentación, crecimiento y mortalidad para estimar los resultados de cada una de las estrategias generadas; junto a la función objetivo multicriterio desarrollada anteriormente. Esto permite que dicho proceso evolutivo avance hacia una estrategia que no solo mejore la rentabilidad del mismo, sino también su sostenibilidad medioambiental y la calidad final del producto.

Resultados

Con el objetivo de validar la utilidad de la metodología desarrollada, ésta ha sido probada con datos reales de producción de Dorada en el Mediterráneo y bajo diferentes escenarios de decisión. Los resultados obtenidos han sido satisfactorios tanto en lo que se refiere a la capacidad de este tipo de técnicas metaheurísticas para abordar el problema, como en cuanto a las potenciales mejoras que su aplicación podría aportar a la actividad acuícola.

En este sentido, los resultados obtenidos han confirmado la hipótesis, muy extendida en la práctica, de que la combinación de diferentes piensos a lo largo del proceso de engorde para adaptar la alimentación de los peces a las condiciones medioambientales, permite mejorar los resultados obtenidos en el proceso de engorde. Además, este proceso de generación y evaluación de diferentes alternativas ha permitido llegar a estrategias que han mejorado otros aspectos, como el impacto de la actividad sobre el medioambiente o la calidad del producto, sin tener un efecto negativo sobre la rentabilidad de la compañía.

## 3.1. Introduction

The exponential and uncontrolled growth of fisheries in the second half of the previous century put the sustainability of fish stocks at risk. Since the 1990s, fishing production has stagnated but there has been an exponential growth of aquaculture. Traditionally, marine fish farming was practiced extensively, mainly in lagoons and coastal ponds. However, production and consumption patterns have changed over time and, nowadays, intensive production is the most used method thanks to the development of new technologies. This change to intensive farming has led to the rapid development of the aquaculture industry, becoming a relevant industry around the world that is able to meet the demand for fish. In this context, sea cage farming has increased its importance in the aquaculture sector in which it has a major comparative and competitive advantage at a global level: the cost reduction, with no energy costs for pumping, aeration, or post-rearing water treatment. In contrast, similar to other areas of the primary sector, fish farms management is complex due to the broad range of internal and external factors that influence the decision-making process. In this way, main decisions throughout the breeding process are affected by the interactions of technical, biological, environmental and economic factors.

Over the last decades, operational research (OR) experts have already developed management tools and Decision Support Systems (DSSs) in order to respond to producers' demands on the automation and optimization of many strategic and operational decisions. In this regard, main company decisions have been also widely analyzed in many OR studies, such as site selection (Stagnitti, 1997), facilities planning and design (Ernst et al., 2000) or hatchery management (Schulstad, 1997). Most of these OR models applied in aquaculture have been traditionally based on accumulated experience in fishing and other primary sector activities, such as agriculture or forestry, to increase the efficiency and profitability of fish farming on an industrial scale (Bjørndal et al. 2004). These tools provide expert information in an easy-to-use manner to end users and, with the technological advance in Big Data and Artificial Intelligence, they have managed to improve aquaculture companies' capacity to make decisions and develop control systems (Zhou et al., 2018).

Among those decisions stands out the selection of the most suitable feeding strategy, since feed is the main operational cost in finfish aquaculture, which can achieve 30%–60% of total production costs (Goddard, 1996). In this regard, great research efforts have been made to determine, from the manufacturer's point of view, the ingredients that would form the optimal feed formulation. This research effort is reflected in several review works, such as those carried out by Kousoulaki et al. (2015), summarizing the current knowledge about nutrition and feed management practices on European sea bass; Sørensen (2012), addressing how ingredient composition and processing conditions affect the fish quality; or De Verdal et al. (2017), analyzing past work to improve feed efficiency using selective breeding. Furthermore, many of these works apply optimization techniques to design an optimal diet composition as, for example, Hormiga et al. (2010) trying to ensure the maximal survival rate of Octopus vulgaris. However, in practice, most producers do not produce their own feed, but rather acquire the feed already formulated by the industry. This, in conjunction with the fact that there are a wide range of feeds in the market, implies that feeding strategies are a complex set of selections of different feeds for the fattening period, also called feeding paths, and, therefore, the number of potential possibilities is extensive and the results of those aspects can vary hugely depending on the final decision.

The central objective of this work is to provide decision makers with a model to address that combinatorial optimization problem. To this end, on the basis that feed selection depends on different factors at the precise moment at which feed is used and it is chosen among a finite set of alternatives provided by specialized manufacturers, metaheuristic techniques stand out as the best alternative to provide a solution. These techniques sacrifice the guarantee to find the optimal solution for the sake of getting good solutions in a significantly reduced amount of time (Blum and Roli 2003) compared to classic optimization techniques, many of whom are not applicable in these problems or lead to computation times too long for practical purposes. For these reasons, the present work applies a genetic algorithm (GA) to feeding decisions in order to generate and evaluate different feeding alternatives based on an objective function. GAs are metaheuristic search and optimization techniques based on principles present in natural evolution that are especially useful in this case since they are designed to work on large spaces involving states that can be represented by strings (Goldberg and Holland, 1988), which is actually the best representation of a feeding path in aquaculture. Furthermore, they perform a multi-directional search by maintaining and combining a population of potential solutions (Michalewicz, 1996), which allows greater flexibility and adaptability to producers' decisions.

GAs are one of the most popular heuristic approaches for optimization with application to many decision areas focused on process and product design, operations planning and control, and operations improvement, as stated in the bibliographical review carried out by Lee (2018). With regard to aquaculture, genetic algorithms have already been used successfully in different optimization problems, as well. Atia et al. (2012) used them to optimally design solar water heating systems and Liu et al. (2011) addressed the water quality prediction using a hybrid approach based on support vector regression and GAs. In this context, there are different applications that have integrated ecological factors in the optimization processes too, such as the prediction of the potential distribution of invader species (Chen et al. 2006), or the prediction of fish distributions (D'Angelo et al. 1995). Lastly, other nature-inspired metaheuristics have been also used successfully in various practical problems related to aquaculture, such as the determination of the production strategies that maximize the present profits of the farming process considering as decision variables the fingerlings size, seeding times and harvesting weights (Cobo et al. 2018). However, despite its application to different aspects of the activity, the enormous potential of these techniques to contribute to the improvement of the efficiency of the feeding decision-making process has still not been adequately exploited.

In this regard, there are still other challenges to be faced. Nowadays, producers should also attend to stakeholders' demands not only in terms of profitability or cost efficiency, but also in terms of environmental responsibility or product quality, aspects that they can sometimes find contradictory. This has led to a lack of management capacity due to the increasing complexity of those decisions and the need for extremely large amounts of data. Consequently, more and more producers demand expert's systems that take into account the new ways of production, such as cleaner production (CP) alternatives, integrating all these criteria with the aim of combining the efficient use of natural resources and the generation of economic profit (Vieira and Amaral, 2016).

In accordance with that objective, the present study integrates a Multiple-Criteria Decision-Making (MCDM) methodology to formulate the fitness function that the genetic algorithm uses to evolve into a near-optimal solution. MCDM problems appear and are intensely applied in many domains where decisions have to be made in the presence of multiple objectives and criteria which usually are in conflict with each other (Tzeng and Huang, 2011). In these situations, decision makers have to select, assess or rank the alternatives according to the weights of the criteria. In the present work, this methodology enables producers to design a feeding strategy according to their subjective perception of the relative importance of many criteria involved in the production process, such as economic, product quality or environmental sustainability ones. In the last decades the MCDM techniques have become an important branch of operations research (Triantaphyllou, 2000; Figueira et al., 2005). Ishizaka and Labib (2011) have already shown the benefits of these methods in establishing rankings of alternatives through various experimental analysis. In addition, the emergence of new ways of production has led to the development of various MCDM tools applied to some problems of aquaculture, such as site selection (Dapueto et al. 2015; Shih, 2017), planning of regional aquaculture development (El-Gayar and Leung, 2001), the optimization of multi-objective bio-economic models in fisheries (Mardle et al. 2000) or the optimization of harvest management strategies of many species, considering interactions between and within species (Stafford 2008), but without analyzing the issue at hand.

The methodology developed in this work represents an innovation in aquaculture since it manages to integrate the use of various optimization criteria, crucial for the development of new ways of production, and the possibility of having a variable feeding path throughout the fattening process in the finfish-feeding decision-making process. After this introduction, the paper is structured as follows. First, section 2 describes the methodological approach, combining MCDM techniques and GA. Then, although the developed methodology could be applied to the culture of many aquaculture species, it is tested in the case of gilthead seabream farming in sea cages in section 3. Lastly, section 4 discuss the results achieved and the conclusions and future research lines are given in section 5.

## 3.2. Materials and Methods

The problem addressed in this study is the determination of feeding strategies in aquaculture farms and, more specifically, in Gilthead seabream farms. For this purpose, a methodology that uses GA and MCDM methodologies has been developed. But, prior to the development of the methodology, the need for specific data and the complex relation between some variables made necessary to clarify the problem and the relational database used, which contains the multiple modules involved in decision-making process. Thus, the described methodology has been implemented in a tool that combines all the techniques required in order to carry out the collection of real data and the simulation and optimization process.

Intensive aquaculture presents good survival and growth rates and an acceptable operating margin compared to traditional extensive aquaculture, but farms management may be particularly difficult sometimes due to the technical, biological, environmental and economic factors that influence the main processes. In the case of Seabream, the production cycle should be divided into clearly defined phases, beginning with the larval rearing and then moving to fry rearing, both of which are conducted within the hatchery, and finally to on-growing (Brown, 2003). The on-growing or fattening process can take place in cages, ponds or tanks, but the main system is the production in sea cages. This process starts by seeding juveniles in sea cages, with densities between 10-20 kg/m$^3$, that will be fed daily with a feed specifically designed for each species. In about one year, they are able to reach first commercial size (300 g) but the exact duration of the breading process depends on many parameters such us the water temperature, some genetic characteristics or the feeding strategy, among others.

The feeding strategy is one of the most important decisions in aquaculture both for its high participation in the total cost of the company and for its influence on the growth of the fish and, therefore, on the future income. This decision implies a long process of research carried out by the feed manufacturers based on the search for an optimal feed formulation. However, when we refer to the feed selection process carried out by the producer, it can be defined as a combinatorial optimization problem, in which the producer has a finite set of feeds {*F1,F2,…,Fm*} and the objective is to select the feed to be used in each week of the fattening period of the selected cage. The decision variables $x_i \in \{1, 2,\dots,m\}$ represent the feed used in week $i$, for $i=1,2,\dots,n$ and a feeding path $X$ is a vector $X \in \{1,2,\dots,m\}^n$. Results obtained for each feeding path are estimated based on the explanatory variables included in the bio-economic model, which will be explained later.

The use of an appropriate database is crucial to allow the tool to easily use specific information but also assists in the clarification of the problem by gaining a detailed understanding of the relationship between variables. In the present case, as can be seen in Luna et al. (2019), the database has a structure consisting of four groups of tables: First, a central axis to identify the aquaculture farm and its main characteristics. Then, two groups representing the uncontrollable variables, such as the water temperature or salinity, 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). Lastly, the group of tables containing the information about the current status of each cage and the specific feeding, growth and loss rates according to the available feeds.

Once the decision problem has been clarified, the methodology is structured as follows:

a. The first step to perform this process is to establish the criteria to be taken into account and weight each one based on the preferences of the farmer using MCDM techniques.
b. Secondly, prior to the process of optimization, the development of a bio-economic model is needed to reasonably simulate the results for each feeding strategy.
c. Lastly, an optimization process is developed based on a multiple-criteria fitness function according to which the initial population of feeding alternatives evolves, with the use of GA's crossover and mutation operators, until finding a useful solution.

### 3.2.1 Criteria selection and weighting

Within the supply of feed for the fattening process, there are notable differences in terms of prices, estimated growth rates and nutritional compositions. Furthermore, feeding strategies are conditioned by other factors, such as the environmental conditions of the farm or even the price variability, and it is therefore difficult to assess their subjective importance or the suitability of each feeding alternative.

#### 3.2.1.1 Proposed criteria

Throughout this section, we explain the three groups of criteria (economic, environmental sustainability, and product quality) used in order to evaluate the feeding alternatives generated by the developed methodology. These criteria have been selected trying to accommodate most of the concerns of aquaculture producers when designing their feeding strategy. The final selection of criteria has been already explained on that published by Luna et al. (2019), where the use of each one and its suitability when selecting a single feed is explained in detail. However, in practice, this methodology allows decision-makers to choose only some of these factors for consideration or add new ones, before ranking them according to their individual needs.

Traditionally, the main objective of most enterprises is profit maximization. Although there are several ways to measure the economic results of a company, in the present case the **operational profit** has been taken as a reference since it is a well-established and easy to interpret indicator. It is defined in the economic submodel as the difference between the costs incurred in the feeding process and the revenue obtained from the sales, 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). This study considers only the feeding costs, making the assumption that others are not influenced by the chosen feed.

On the other hand, as an alternative to that conventional point of view, sustainable and organic procedures aim to reduce the negative environmental impacts of aquaculture production. In this regard, sharing best practices and their application in aquaculture companies throughout the breeding process is a key determinant, as well as the appropriate selection of feed producers, as they also use energy and emit carbon dioxide (Boyd, 2015). The environmental sustainability criteria have been divided into three sub-categories:

- Official ecolabels have been designed to certify organic products from a trusted third party. The Commission Regulation (EC) No 889/2008 of 5 September 2008 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, the maximum stocking density is 15 $kg/m^3$ for sea bass and seabream. This label involves a disadvantage for the high cost of certification.
- In contrast, many consumers and producers prefer other strategies related to the environment surrounding aquaculture farms. Lembo et al. (2018) showed that in order to minimize the environmental impact of aquaculture, stakeholders placed the highest value on the prevention of **nitrogen and phosphorus** waste, and on the increase of feed efficiency in terms of fish meal and oil used. In this case, the feed efficiency is represented by the **Fish-in Fish-out ratio**, the amount of fish based feed needed to produce a unit weight of the cultured species.
- Along these lines, prior to the arrival to the farm, feed production has also an environmental impact that is commonly measured by the **energy use** (MJ equiv.), and the **global warming potential impact** ($CO_2$ equiv.) of the greenhouse gas emissions, among others (Abdou et al., 2017).

Lastly, fish products quality is easily perceived by the appearance, odor, flavor, and texture but it is still very difficult to contemplate objective criteria in this area. Several studies, such as Shahidi and Alasalvar (2010), have explained that fatty acids, particularly **omega-3**, are considered as health-promoting dietary components. In this regard, some feed producers present an approximate amount of omega-3 transmitted with the use of their feed during the whole fattening process based on their own empirical studies. Besides that, Grigorakis (2010) has shown that 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. These two criteria have been included as an approach to two different points of view about the maximization of the fish quality.

Once selected, the corresponding criteria are organized into a hierarchical structure (Fig. 1) which will facilitate the evaluation of their relative importance.

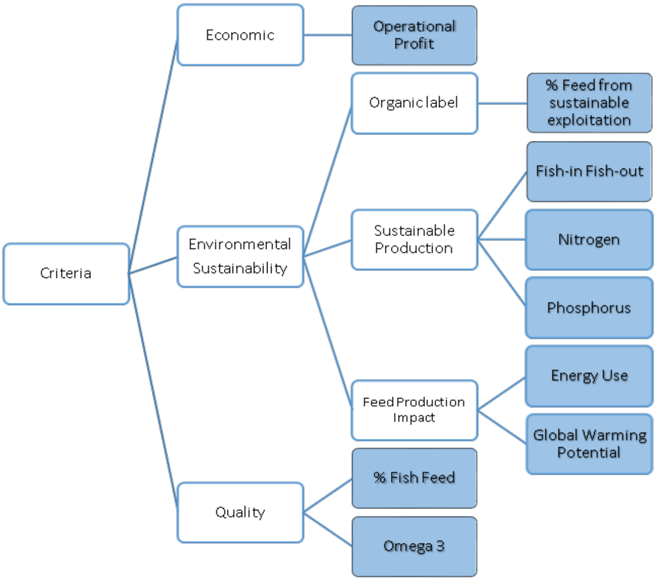


Fig. 1 Criteria hierarchy (Luna et al., 2019).

### 3.2.1.2 Weighting method

The developed methodology uses the Analytic Hierarchy Process (Saaty, 1980) to turn human judgments in numerical values that will be easily integrated in a final weight for each criterion. That process is based on a series of pairwise comparisons, in which the decision-maker states his preferences by comparing all criteria and subcriteria with regard to same level decision elements, using a 1-9 numeric scale in order to establish priority values $a_{ij}$ for each pair of criteria (Table 1).

| Intensity | Importance of one over another | Explanation |
|---|---|---|
| 1 | Equal Importance | Two activities contribute equally to the objective |
| 3 | Moderate importance | Experience or judgment slightly favor one criterion over another |
| 5 | Essential or strong importance | Experience or judgment strongly favor one criterion over another |
| 7 | Very strong important | 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 order of affirmation |
| 2,4,6,8 | Intermediate values | When compromise is needed |

Table 1: AHP Marks Interpretation - Saaty (1987)

If the element $E_i$ is preferred to $E_j$ then $a_{ij}>1$. At each level of the criteria hierarchy an *n*-dimensional squared matrix, where the pairwise comparison values are stored, is obtained in which the reciprocal properties $a_{ij}=1/a_{ji}$, $a_{ii}=1$ and $a_{ij}>0$ always holds. In such a way, each entry $a_{ij}$ represents the importance of the $i^{th}$ criterion relative to the $j^{th}$ criterion (1).

$$C = \begin{bmatrix} 1 & a_{12} & \dots & a_{1m} \\ 1/a_{12} & 1 & \dots & a_{2m} \\ \dots & \dots & 1 & \dots \\ 1/a_{1m} & 1/a_{2m} & \dots & 1 \end{bmatrix} \quad (1)$$

Furthermore, the AHP model also proposes to estimates a measure of the consistency in the decision maker's judgments (Wang et al., 2007). The consistency analysis seeks to ensure that the judgments of the decision maker are coherent from a logical point of view. In order to contrast the consistency of comparative judgments between the criteria, Saaty (1980) defined an inconsistency ratio and recommends values of 0.1 or lower so that pairwise comparisons can be considered acceptable. Another consistency check is a weak consistency condition that checks whether if $a_{ij}>1$ and $a_{jk}>1$ then $a_{ik}>=max(a_{ij},a_{jk})$ for every $i,j,k=1,2,\dots,n$..

As simultaneously optimizing all the criteria is impossible, it is necessary to group these subjective judgments of the decision-maker on the importance of the criteria and from there define a heuristic process of searching for good solutions. In this regard, the developed methodology aggregates the values to form a vector of relative weights for each criterion considered in the matrix. In the present case, the weight vector is estimated as the normalized components of the eigenvector corresponding to the largest eigenvalue of the matrix, according to the Saaty's approach. To address that process, the application of the AHP methodology has been developed based on Cabral et al. (2016).

### 3.2.2 Bio-economic simulation

In order to simulate the fattening process for each alternative of feeding and estimate its results or consequences, a bio-economic model has been developed. In this regard, the bio-economic model of the process of farming in sea cages integrated into the present work is based on the model proposed by Llorente and Luna (2013, 2014) and Cobo et al. (2015).

Initially, that model consisted in a biological sub-model of the process of farming in sea cages, which considers feed and growth rates as a percentage of the weight of the fish depending on the weight and environmental conditions, and an economic submodel that quantifies the revenue and costs involved. However, MCDM techniques explore new factors, such as those related to environmental sustainability or product quality that affect the decision-making process in aquaculture. As a consequence, the bio-economic model has gone one step further to estimate every important factor, based on the characteristics of each feed, while the biological process is simulated. In this regard, it also takes the assumption that producers cannot address the control of any of the abiotic factors affecting the growth process, for example, temperature, light, salinity, and oxygen, in an economically efficient way (Brett, 1979). Neither is it possible to choose the maximum biomass density, which is equal to the maximum insurable biomass density (Luna, 2002) or to the maximum allowed density in the case of organic labelled production.

However, some different assumptions have been taken. First of all, now it is possible to change the feed during the fattening process in order to reach the farmer goals. In this way, some farmers use a different feed during the colder months trying to maintain the growth and mortality rates or to reduce costs. On the other hand, the model considers only one a time investment, in which producers will take the harvesting time decision attending to their economic needs or agreements, so harvesting weight will be slightly different for each feeding strategy. Nevertheless, this methodology is also adaptable to a different model that considers an infinite series of investments or time-dependent harvesting. In addition, the developed methodology allows decision-makers to consider, when such data is available, specific functions based on empirical findings in aspects such as feeding, growth, loss or dispersion.

Thus, feed composition and quality are considered crucial variables, dependent on the feed selected by the producer and the total amount consumed, since they will be used to simulate the economic, environmental and quality factors of each alternative on a daily basis. Finally, they are summed for the whole period getting as many values for each criterion as alternatives are generated in the optimization process.

### 3.2.3 Optimizing feeding strategies

Genetic algorithms are search algorithms based on the mechanics of natural selection and natural genetics. GAs starts with a random population of strings, known as chromosomes, and thereafter successive populations are generated. To perform an effective search for better and better structures, they first require payoff values (objective function values) associated with individual strings (Goldberg, 2012).

In this regard, there are also different evolutionary metaheuristic techniques that can be used to address multiple-criteria problems, some of them using genetic algorithms such as NSGA-II (Deb et al., 2002). These techniques are mainly oriented to obtain a well-distributed set of non-dominated solutions that approximate the Pareto front in practical problems in a great variety of fields. In fact, evolutionary multi-objective optimization is one of the most active fields of research within evolutionary computation (Abraham et al., 2005).

However, evolutionary multi-objective algorithms usually require working with a small number of objectives, because when this number grows there is an exponential increase in the number of non-dominated solutions found by the algorithms, which blocks the mechanism they have to reach the solutions of the Pareto front (Ishibuchi et al., 2008). In practice, these evolutionary algorithms are not very useful for the resolution of problems with more than three objective functions, so in the present work, we have chosen to combine the objectives in a fitness function with an MCDM technique and thus approach the problem with GAs.

3.2.3.1 Evaluation function

Genetic algorithms require an optimization objective according to which the population evolves. The fulfillment of this objective is measured by the fitness function *F(X)*, which assigns a fitness value to each individual based on the parameters derived from its chromosome. In the present study, that function is built for each feeding path taking the Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) as a reference (Hwang and Yoon, 1981).

Traditionally, TOPSIS considers two hypothetical alternatives: one with the best values for all the attributes (the positive-ideal) and one with the worst values for all the attributes (the negative-ideal), to later apply the fitness function for each alternative. Based on the definition of those ideal solutions, depending on each producer's profile, it is possible to obtain a ranking of alternatives. The ranking of alternatives depends on the attainment of relative proximity indexes using a TOPSIS approach which allows us to construct the relative proximity intervals.

This fitness function is, therefore, defined as the relative closeness to the ideal solution:

$$F(X) = \frac{d^{-}(X)}{d^{-}(X) + d^{+}(X)} \qquad (2)$$

where $d^{-}(X)$ and $d^{+}(X)$ represents the separation of criteria values of *X* from the negative ideal and positive ideal solutions, respectively. This ratio varies between 0 and 1 and alternatives with a ratio closer to 1 would be preferred. Accordingly, and from the best alternatives, the optimization algorithm continues generating new solutions in order to evolve to a near-optimal one (Lamata et al., 2016).

In the present study, a TOPSIS has been integrated in an evolutionary methodology. This causes that there are not a fixed number of combination or alternatives, but they are generated sequentially. In order to overcome this problem, two hypothetical ideal alternatives, positive and negative, are generated from an initial step where only one feed can be used during the whole period. This enables to estimate the initial values for each criterion, as many as feeds are available, and to generate the hypothetical alternatives with the best and worst values with a supplement of ±75%, assuming that a combination of different feeds will achieve better results than the utilization of only one. The only exception is the criterion of organic production feed ratio, whose ideal value is considered 1 and the anti-ideal value 0.

3.2.3.2 Evolving process

Once the fitness function has been fixed, the process continues with the generation of a random set (population) of feeding paths (individuals) and an estimation of their fitness according to that evaluation function. The second step of the GA methodology is to improve the initial population sequentially. This algorithm receives three operators to guide the algorithm towards a solution to the given problem:

a. Selection: The selection process determines which individuals participate in reproduction to generate the next population according to their fitness values. In general, this process takes advantage of the fittest solutions by giving them greater weight when selecting the next generation and hence leads to better solutions to the problem (Siriwardene and Perera, 2006).
   The developed methodology includes an elitism factor. Elitist selection strategies ensure that a percentage of the fittest alternatives continue to the next generation without any crossover or mutation. Once again, the disadvantage is the possibility of genetic convergence but some studies have proven that elitism appears to be an important factor to improve evolutionary multiple-objective optimization (Parks, 1996; Zitzler et al., 2000).

b. Crossover: the classic genetic crossover is performed using a random crossing point to create new individuals for the next generation by taking more than one parent solutions and combining them into a child solution. A high crossover rate encourages good mixing and the genetic algorithm is more likely to create a better solution.

c. Mutation operators. The mutation randomly changes the feed of a week encouraging genetic diversity amongst solutions. High mutation rates prevent GA from converging to a local minimum but it could destroy good solutions.

Furthermore, to initiate the process it is necessary to assign the value of certain parameters, such as the crossover and mutation probabilities or the size of the population. The population size is the number of individuals that form part of each set generated. More individuals mean more cost, in time, but also increase the population diversity.

During this process, each solution, therefore, needs to be awarded a score, to indicate how close it came to meeting the overall specification of the desired solution, by applying the fitness function (2). This score, allow the process to decide the optimum moment to stop, by a stopping criterion, instead of continuing during a fixed number of generations. The stopping criterion is settled as a number of generations without any improvement and when it is met, the algorithm provides the final set of feeding strategies.

Finally, the ranking of the alternatives is presented with information about the feed to be used each week and the values of each criterion in the final alternatives are provided to the decision maker.

### 3.3. Application to gilthead seabream feeding strategies

Once the methodology has been developed, the process of selecting the optimal feeding strategy has been tested for two theoretical scenarios on decision-makers' preferences. Results for the selected strategy in each of those scenarios will be simulated for the case of a gilthead seabream farm in the Mediterranean during a period of 52 weeks and with the possibility of using three different feeds currently available in the market. As will be explained below, information used has been collected from primary sources, such as oceanographic buoys or feed manufacturers, or secondary sources of information, i.e., other research studies.

Therefore, the simulation process starts with the collection of relevant data, both from the farm and from external factors, and the estimation of the final weights for all the criteria in each scenario. Secondly, an objective function is calculated with the bio-economic model. Then, the process of optimization is developed with the generation and evaluation of alternative feeding paths in order to find an optimum strategy. Lastly, as a discussion of the utility of this methodology, results for the first scenario are compared with the alternative of using only the most adequate feed.

### 3.3.1 Farm information

First of all, the specific characteristics of one farm of gilthead seabream have been simulated (Table 2) based on common characteristics of Mediterranean farms in Spain. In this way, the problem to optimize would be the performance of a unique sea cage of Gilthead seabream with juveniles of 30g during a year. The maximum biomass density depends on the type of production as the regulation requires, generally being 20 Kg/m$^3$ unless in the case of organic production where it would decrease to 15 kg/m$^3$.

External factors included in the database are the water temperature and the characteristics of the available feeds. Information on sea temperature has been collected from the oceanographic buoys network of the Spanish Port Authority, that covers the principal locations of marine aquaculture in Spain. In the present study, only the data registered during 2017 by the buoy placed at the simulated location, in the Mediterranean Sea near Tarragona (Fig. 2), have been used.

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

Table 2: Farm Characteristics

Fig. 2 Port Buoy 2720 (Source:mapswire)

Regarding the feeding alternatives, the main rates and characteristics have been estimated based on the information provided directly by the feed producer (table 3). However, there is one exception: feed production impact criteria have been estimated based on the study conducted by Pelletier and Tyedmers (2007). In that study, the approximate value for both "feed production impact criteria" depending on the feed ingredients as the aggregated impact in raw material production, processing and transportation stages. All this information has been obtained for three different feeds:

- Feed 1 (F1) represents the more commonly used feed since it performs well under normal circumstances and it is available at a very competitive price.
- Feed 2 (F2) have an increased percentage of fish protein so, although it has a higher price, growth rates are good even under unfavorable weather conditions.
- Feed 3 (F3) is a high quality and price feed, entirely made with products from organic fisheries/production. This feed presents always better results, especially in warm conditions.

| Feed Info | F1 | F2 | F3 |
|---|---|---|---|
| Price USD/Kg | 1.11 | 1.19 | 1.49 |
| Fish origin feed (%) | 25 | 38 | 55 |
| Plant origin feed (%) | 50 | 62 | 45 |
| Poultry origin feed (%) | 25 | 0 | 0 |
| Organic Feed (%) | 0 | 0 | 100 |
| Total Nitrogen (g per kg of feed) | 77.5 | 73.6 | 99 |
| Total Phosphorus (g per kg of feed) | 16.3 | 16.8 | 17.5 |
| 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

### 3.3.2 Theoretical scenarios of producer's preferences

Once the main conditions have been specified, two theoretical scenarios of producer preferences have been simulated for such a farm. To estimate the final weights in each scenario, criteria are compared by pairs, scoring the importance of each criterion related to another one. In the present study, two conflicting tendencies have been analyzed with respect to fish production: the traditional production procedures with the only objective of maximizing the annual profit and the organic production trend commonly used to differentiate the product with an organic label, which constitute an alternative to conventional aquaculture.

The scoring process follows a hierarchical structure, starting from the big groups of criteria and ending on the disaggregated criteria. This system reduces the number of evaluations just to the values under the main diagonal inasmuch as the others are deducted by the property of reciprocity ($a_{ji}=1/a_{ij}$):

- First of all, when comparing the three groups of criteria (table 4), the economic criterion is evaluated with the highest value in the first scenario, while the group formed by the environmental sustainability criteria is the most important in the second one.

| Scenario 1 | | | | Scenario 2 | | | |
|---|---|---|---|---|---|---|---|
| | $C_1$ | $C_2$ | $C_3$ | | $C_1$ | $C_2$ | $C_3$ |
| $C_1$ | 1 | 9 | 9 | $C_1$ | 1 | 1/9 | 1/2 |
| $C_2$ | 1/9 | 1 | 1 | $C_2$ | 9 | 1 | 4 |
| $C_3$ | 1/9 | 1 | 1 | $C_3$ | 2 | 1/4 | 1 |
| Consistency Index = 0.0 | | | | Consistency Index = 0.0 | | | |
| *$C_1$=Economic criteria; $C_2$=Environmental criteria; $C_3$=Quality criteria | | | | | | | |

Table 4: Pairwise judgments – main groups

- Secondly, the environmental sustainability criteria have been evaluated in both scenarios. In the first one all the environmental criteria have low importance and only the fish-in:fish-out stands out inasmuch as it represents an efficiency ratio. On the other hand, the criterion that has a more prominent weight in the second scenario is the proportion of feed produced by organic production as requires the European Commission Regulation for the labeling of organic products (table 5). In practice, this requirement will condition the final choice since only one feed fully complies it.

| | **Scenario 1** | | | | | | | **Scenario 2** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $C_{2.1}$ | $C_{2.2}$ | $C_{2.3}$ | $C_{2.4}$ | $C_{2.5}$ | $C_{2.6}$ | | $C_{2.1}$ | $C_{2.2}$ | $C_{2.3}$ | $C_{2.4}$ | $C_{2.5}$ | $C_{2.6}$ |
| $C_{2.1}$ | **1** | 1/9 | 1/3 | 1/3 | 1/6 | 1/6 | $C_{2.1}$ | **1** | 9 | 9 | 9 | 9 | 9 |
| $C_{2.2}$ | **9** | **1** | 3 | 3 | 2 | 2 | $C_{2.2}$ | **1/9** | **1** | 1 | 1 | 1 | 1 |
| $C_{2.3}$ | **3** | **1/3** | **1** | 1 | 1/2 | 1/2 | $C_{2.3}$ | **1/9** | **1** | **1** | 1 | 1 | 1 |
| $C_{2.4}$ | **3** | **1/3** | **1** | **1** | 1/2 | 1/2 | $C_{2.4}$ | **1/9** | **1** | **1** | **1** | 1 | 1 |
| $C_{2.5}$ | **6** | **1/2** | **2** | **2** | **1** | 1 | $C_{2.5}$ | **1/9** | **1** | **1** | **1** | **1** | 1 |
| $C_{2.6}$ | **6** | **1/2** | **2** | **2** | **1** | **1** | $C_{2.6}$ | **1/9** | **1** | **1** | **1** | **1** | **1** |
| Consistency Index = 0.0027 | | | | | | | | Consistency Index = 0.0 | | | | | |

* $C_{2.1}$=Organic Feed (%); $C_{2.2}$=Fish-in Fish-out; $C_{2.3}$=Total Nitrogen (g); $C_{2.4}$=Total Phosphorus (g); $C_{2.5}$=Energy Use (MJ equiv.); $C_{2.6}$=Global Warming (kg CO2 equiv.)

Table 5: Pairwise judgments – environmental sustainability criteria

- Lastly, although a minimum quality is always required when selling fish products, quality criteria during the whole process are more important under the circumstances of differentiation, second scenario, than for a producer focused on economic performance as in the first scenario (table 6).

| | **Scenario 1** | | | **Scenario 2** | |
|---|---|---|---|---|---|
| | $C_{3.1}$ | $C_{3.2}$ | | $C_{3.1}$ | $C_{3.2}$ |
| $C_{3.1}$ | **1** | 1/9 | $C_{3.1}$ | **1** | 1/8 |
| $C_{3.2}$ | **9** | **1** | $C_{3.2}$ | **8** | **1** |
| Consistency Index = 0.0 | | | Consistency Index = 0.0 | | |

*$C_{3.1}$=% Fish origin feed; $C_{3.2}$=Omega 3

Table 6: Pairwise judgments – product quality criteria

After applying the AHP methodology, the weights associated with each criterion in each scenario are those shown in Table 7. As can be observed, the distribution of weights perfectly fulfils the perception of the relative importance of the criteria in the proposed scenarios. The feeding strategy selected for the first scenario will mainly depend on the economic benefit for the company, while in the second case, the most important criterion will be the achievement of an ecological label. This method greatly facilitates the evaluation work that could be very difficult to do directly on all of the criteria.

| Criterion | Scenario 1 | Scenario 2 |
|---|---|---|
| **Economic Criteria** | **81.8%** | **8.3%** |
| Profit | 81.8% | 8.3% |
| **Environmental Criteria** | **9.1%** | **75.0%** |
| % Organic Feed | 0.3% | 48.2% |
| Fish-in Fish-out Ratio | 3.2% | 5.4% |
| Total Nitrogen | 1.0% | 5.4% |
| Total Phosphorus | 1,0% | 5.4% |
| Energy Use | 1.8% | 5.4% |
| Global Warming Potential | 1.8% | 5.4% |
| **Quality Criteria** | **9.1%** | **16.7%** |
| % Fish origin feed | 0.9% | 1.9% |
| Omega 3 | 8.2% | 14.8% |

Table 7. AHP weights in both scenarios considered.

### 3.3.3 Objective function

In order to carry out the optimization process successfully, a fitness function, which evaluates how close a given solution is to the objective solution, is needed. In this particular case, the objective function is the business goal of the selected farm, in mathematical terms, of the multiple and competing criteria combined.

Both the process of estimation of the results for one feed alternatives in order to find the objective function and the evaluation of each alternative generated by the genetic algorithm involves two steps where the bio-economic model takes action. In the first instance, it estimates the growth reached and the feeding amount needed on a daily basis. Then, the value of each criterion is calculated from that data.

In economic terms, profit is quantified both in unitary and aggregated terms, by the revenue and costs involved. Cost varies as a function of the used feeds, due to its different feeding amount and price. Meanwhile, revenue depends on the reached growth, its dispersion if available and the selling price, which relies on the type of production. For classical aquaculture, weekly selling prices correspond to the main

Spanish wholesale market prices for the commercial classes of Seabream (300–400g, 400–600g, 600–1000g) 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% and 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.

In the case of all other additional criteria mentioned above, grouped as environmental sustainability and product quality criteria, they can be estimated based on the information provided by the different feed producers as a percentage of the amount used of each feed.

As a result of this process, the main values for each alternative are estimated. Data shown in table 8 for the first scenario provides an idea of the importance of choosing an adequate feeding path, being able to distinguish clearly different results for each criterion. These results confirm the characteristics of the three different feed mentioned above. In the case of positive-ideal and negative-ideal, they are multiplied by ±75% setting the objective functions. On the other hand, scenario two shows similar results with a reduction due to the smaller number of fishes seeded to meet the organic regulation requirements.

| Criterion | Obj | F1 | F2 | F3 | **+ Ideal** | **- ideal** |
|---|---|---|---|---|---|---|
| **Economic Criteria** | | | | | | |
| Profit ($) | MAX | 9,921.03 | 9,613.06 | 8,067.96 | **17,361** | **2,016** |
| **Environmental Criteria** | | | | | | |
| Organic Feed (%) | MAX | 0% | 0% | 100% | **1** | **0** |
| Fish-in Fish-out Ratio | MIN | 52% | 77% | 105% | **13%** | **183%** |
| Total N (g) | MIN | 650,069.23 | 604,280.52 | 567,337.66 | **157,912** | **1,585,360** |
| Total P (g) | MIN | 136,724.24 | 137,933.60 | 100,286.96 | **34,181** | **280,240** |
| Energy Use (MJ equiv.) | MIN | 163,154,800 | 80,861,140 | 227,074,800 | **2.02E+07** | **3.97E+14** |
| Global Warming (kg $CO_2$ equiv.) | MIN | 13,966,000 | 6,865,731 | 15,601,950 | **1.72E+06** | **2.73E+13** |
| **Quality Criteria** | | | | | | |
| % Fish origin feed | MAX | 25% | 38% | 55% | **96%** | **6%** |
| Omega 3 (%) | MAX | 1.02% | 1.49% | 1.73% | **3.50%** | **0.25%** |

Table 8: hypothetical ideal alternatives for scenario 1.

Then, as stated in the methodological approach, the fitness is calculated as the relative closeness to those ideal solutions (2).

### 3.3.4 Search for useful solutions

Once the objective function and the method responsible for evaluating each alternative of the feeding strategy have been determined, the genetic optimization process begins with the search of useful solutions, based on the generation of alternatives and the evolution till the point where a better solution is not found in a determined number of generations. For the evolving process, the following parameters have been considered: population size of 30, crossover probability of 0.8, mutation probability of 0.03 and a limit of 15 generations without any improvement to stop the process. Furthermore, the best individual is always included in the next generation.

After applying the genetic algorithm with the parameter defined above a set of 30 potential solutions is obtained for each generation, which means that more than 1900 alternatives for each scenario have been evaluated. This means that, in most cases, one of the problems faced by this type of tools is the computational cost, measured as the time needed to finish the process. But, in the present work, results have been obtained using an Intel Core i7 2.81GHz processor and 16 Gb SDRAM, and the average execution time was only 210 seconds (table 9).

| Scenario | Generations | Number of alternatives | Execution time (seconds) |
|---|---|---|---|
| First | 64 | 1920 | 293.25 |
| Second | 68 | 2040 | 333.65 |

Table 9: Simulation numbers.

Regarding the proper functioning of the evolutionary process, as can be seen in figures 3a and 3b, in both cases the genetic algorithm has managed to show some improvement in the fitness quality (relative closeness to the ideal solution) of the feeding alternatives.

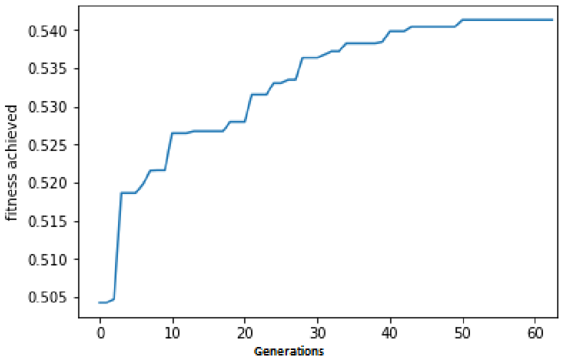


Fig. 3a Evolution of the average fitness for scenario 1.

With respect to the fitness value and how it has been achieved, although both scenarios start from an intermediate value corresponding to the first randomly generated alternatives, there are some differences between them. While the first scenario seems to improve the fitness only a little bit after 60 generations (Fig. 3a), in the second one a relevant improvement is achieved (Fig. 3b). However, this does not necessarily mean that results for the second scenario are better than for the first one, but that it has managed to get closer to the option proposed in that scenario as the ideal one.

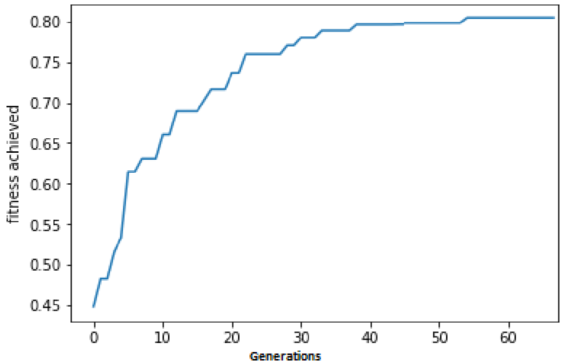

Fig. 3b Evolution of the average fitness for scenario 2.

In addition, the algorithm provides the decision maker with the best feeding strategy generated during the iterative process (Table 10) and the final set of 30 potential solutions. This allows the decision-maker to compare the new feeding strategy, obtained with the option of combining different feeds along the breading process, with the traditional one-feed alternatives and results of each of them for the economic, environmental and quality criteria can be analyzed. Furthermore, the fact of offering to the decision-maker a set, or population, of good alternatives or near-optimal schedules facilitates the final decision and allows considering new factors not initially included in the model.

| Scenario | Best solution – Feeding path | Fitness |
|---|---|---|
| First | {F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F1, F3, F1, F3, F1, F3, F2, F1, F1, F1, F1, F1, F3, F2, F2, F1, F1, F1, F1, F1, F1, F1, F1, F2, F1, F2, F2, F2, F2, F2, F2, F2, F2, F2, F2, F2, F2, F2, F2, F2, F2} | 0.54218 |
| Second | {F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F1, F3, F3, F3, F3, F3, F3, F3, F2, F3, F3, F3, F1, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3, F3} | 0. 8028 |

Table 10: Best solutions for both scenarios.

The feeding strategy proposed for each scenario can be seen more graphically in figures 4a y 4b, which shows the evolution of the water temperature (left side) over the whole period and the recommended feed (right side) for each week.

In this regard, the best alternative for the first scenario is a mix of the three feeds (Fig. 4a). The algorithm recommends first the F3 feed, probably due to its better growth rates in warm conditions, but it changes to F2 feed, which has similar results under cold conditions, when the water temperature decreases. In the mid-term it recommends the cheaper one, generating a saving in feeding costs. In this case, although the ideal solution seems not to be very close, it can be assured that the best alternative is a combination of several feeds to take advantage of their qualities at each moment of the process.

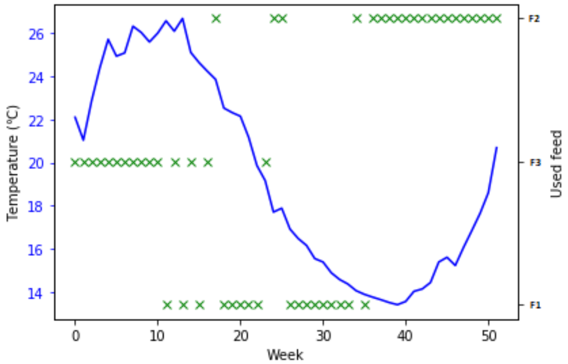


Fig. 4a Selected feed and weekly temperature scenario 1.

However, in the second scenario (Fig. 4b) the algorithm mainly recommends the use of F3, since it is the only available feed that can be used for organic production. This explains why the ideal alternative and the solution reached are closer than in the other case, since both refer mainly to the criterion of organic labelling. This allows us to conclude that in a scenario like this, in which the producer needs to fulfil a specific requirement, the number of valid feeding alternatives is greatly reduced and the evolutionary process would simply lead to the option in which only the feed that comply with that requirement is used.

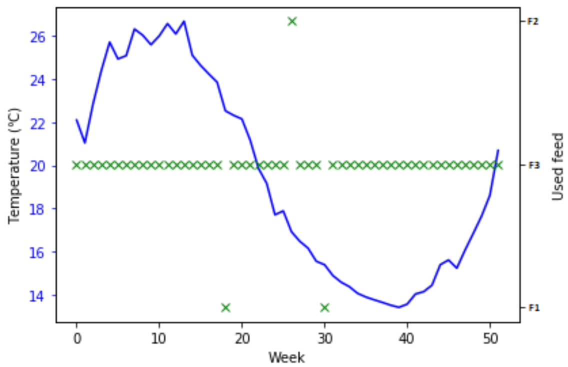


Fig. 4b Selected feed and weekly temperature scenario 2.

These results confirm that the methodology developed is useful when setting a production objective in a complex environment where diverse and sometimes conflicting criteria intervene. In addition, the fitness function and the genetic algorithm have worked at the time of optimizing feeding strategies, evolving from the first generation and finding a good solution in an adequate time.

## 3.4. Discussion of the mixed strategy selected for the first scenario

After assessing the capacity of the developed methodology to analyze and prioritize new alternatives properly, some features that are relevant shall be discussed thoroughly. The most important is the validation of the hypothesis that a combination of different feeds should improve the results obtained with only one feed during the whole period. This requires a comparison between the selected mixed strategy for the first scenario and the unique feed that the tool would have chosen if so requested. Secondly, the stability and sensibility of the outcomes that the developed methodology obtains have been tested. It should be taken into account that there is no point in discussing the results for scenario 2, corresponding to organic production, since the methodology has led to the use of a one-feed strategy.

On the one hand, results for the first scenario are conclusive, the mixed strategy found by the developed methodology has resulted in significant gains in the improvement of the selected criteria, therefore confirming the initial hypothesis. In this case, the criterion with the highest importance is the economic one and it shows an improvement of 7.17% compared to the value estimated for F1 feed. As can be seen in table 11, although there has been an increase in producer's costs, the increase in the weight achieved, and therefore in the benefits obtained, compensates the situation. Furthermore, product quality, where the second most important criterion can be found, becomes significantly larger. However, the results for the environmental sustainability criteria, which are not very important in this case, have worsened.

| Scenario 1 | F1 | Mixed Strategy | Var. | Result |
|---|---|---|---|---|
| Fishes | 12,141 | 12,144 | 0.02% | Improvement |
| Unit weight reached | 329.28 | 370.19 | 12.42% | Improvement |
| Total weight (Kg) | 3,997.82 | 4,496 | 12.45% | Improvement |
| Cost ($) | 9,341.17 | 11,028.29 | 18.06% | Worsening |
| Cost per kg | 2.06 | 2.16 | 4.99% | Worsening |
| Revenue ($) | 19,262.20 | 21,660.39 | 12.45% | Improvement |
| Revenue per kg | 4.82 | 4.82 | - | - |
| FCR (%) | 210% | 192% | -8.50% | Improvement |
| **Economic Criteria** | | | | |
| Profit ($) | 9,921.03 | 10,632.10 | 7.17% | Improvement |
| **Environmental Criteria** | | | | |
| Organic Feed (%) | 0% | 25% | (+25%) | Improvement |
| Fish-in Fish-out Ratio | 52% | 75% | 42.94% | Worsening |
| Total N (g) | 650,069.23 | 722,507.69 | 20.90% | Worsening |
| Total P (g) | 136,724.24 | 149,525.28 | 11.14% | Worsening |
| Energy Use (MJ equiv.) | 163,154,800 | 151,911,800 | 1.98% | Worsening |
| Global Warming (kg $CO_2$ equiv.) | 13,966,000 | 12,036,020 | 8.55% | Worsening |
| **Quality Criteria** | | | | |
| % Fish origin feed | 25% | 39% | 56.22% | Improvement |
| Omega 3 (%) | 1.02% | 1.27% | 24.99% | Improvement |

Table 11: Improvements achieved – scenario 1.

This results can be more easily compared in figure 5. As an added benefit, it is possible to highlight that the company can't sell the fish until they reach the minimum weight for sale in the market (300 g) and in this case, it is reached several weeks before with the mixed strategy. This would give the producer greater flexibility and the capacity to react to possible adverse situations, which can be considered a measure that significantly reduces the risk incurred.

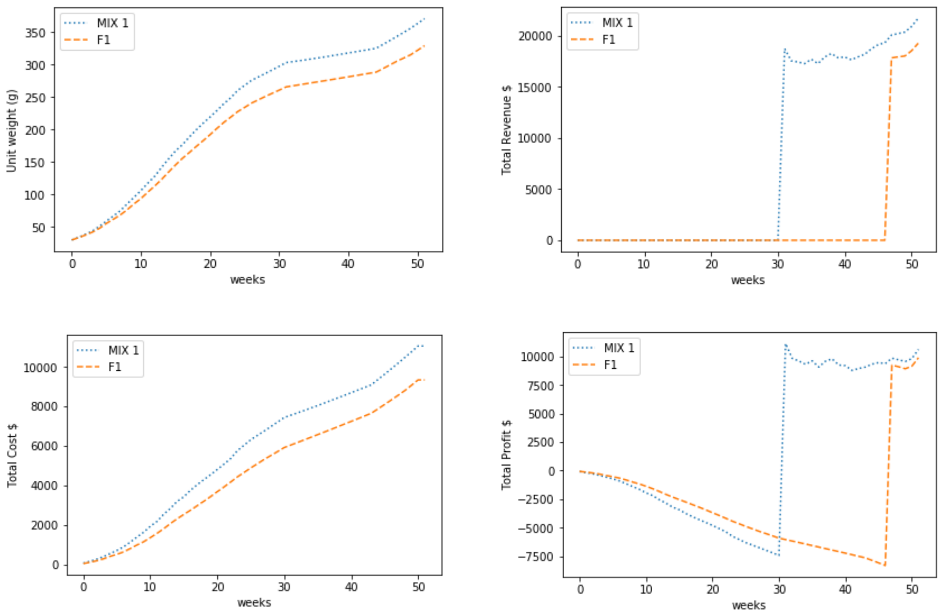


Fig. 5 Visual comparison of strategies – scenario 1.

On the other hand, the proper functioning of the genetic algorithm has been analyzed in two steps: First, 100 executions were carried out with the initial parameters, described in the previous section, in order to evaluate the stability of the results obtained. This analysis allows us to test the ability of GA to reach a similar feeding alternative.

Regarding the fitness reached at the different times, there can be assurance that, as long as the current conditions are maintained, the feeding alternative selected will reach a similar fitness, resulting in the above mentioned increase in the company results.

| **Runs** | **Mean** | **Std deviation** | **Max** | **Min** |
|---|---|---|---|---|
| 100 | 0,5428 | 0,0016 | 0,5467 | 0,5378 |

Table 12: Stability analysis.

In addition, it is also possible to check that most feeding alternatives selected by the evolutionary process, in the 100 executions carried out, follow the similar pattern: a first phase using the F3 followed by a short phase of use of the F1, and a final phase where the vast majority of alternatives uses the F2. For this purpose, the figure 6 shows the how many times each feed has been chosen in each week. In this analysis, although the stability of the evolutionary search process is confirmed, it can be seen that in each phase there are some loose weeks in which a different feed is chosen. In practice, this type of outliers should be eliminated, either automatically or manually by the decision maker, given the inefficiency of changing feed for such a short period (one week).

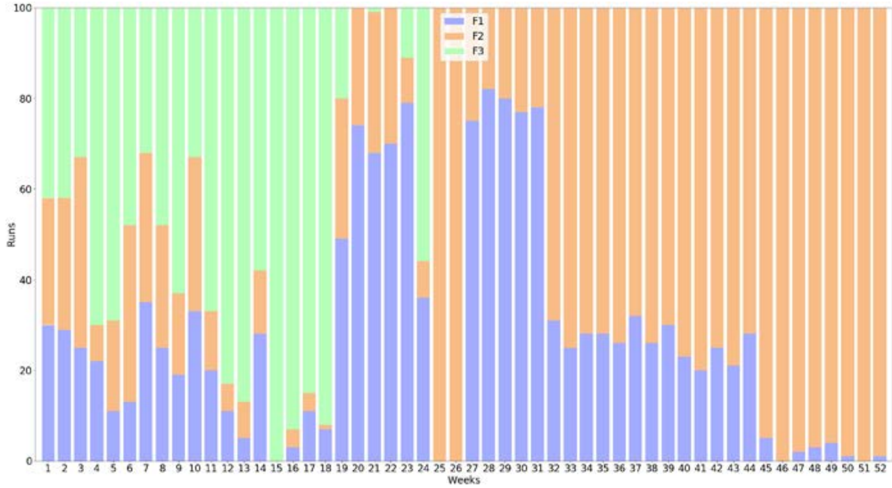


Fig. 6 Number of runs out of 100 in which each feed has been chosen.

Secondly, in order to analyse the sensitivity, how a small change in the operators to guide the algorithm could change the fitness reached was evaluated. In this case, a change in the stop criterion, the limit of executions without finding a better alternative, has been analyzed. As can be seen in the figure 7, although the results are made worse when the stop criterion is very low, the fitness variation is very low and there is a point, around 15 generations, when the fitness is stabilized.

These results have allowed us to set the stop criterion in 15 generations, obtaining good results without unnecessarily increasing the execution time, which could lead to inefficiencies. This analysis has been carried out both for the case of the total number of executions and the number of individuals per generation, with similar results. That points out to future applications of this methodology, where the value of these parameters could be optimized simultaneously in order to find the values that can find the optimal solution in the shortest amount of time, thus increasing the efficiency.

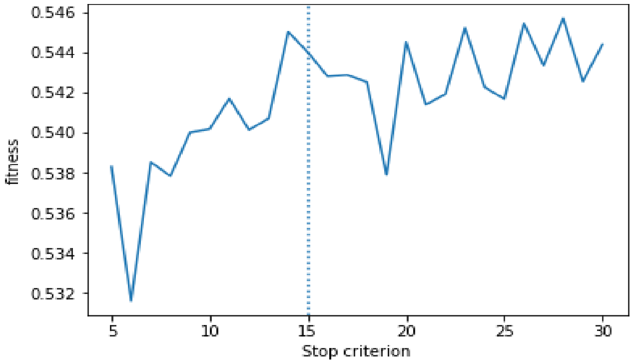


Fig. 7 Sensibility analysis.

### 3.5. Conclusions

In recent years, aquaculture has become a relevant industry called to meet the world demand for fish, though not without difficulty. As is the case with many primary sector activities, the management of fish farms is increasingly complex due to the broad range of internal and external factors that influence most decisions and the need for managers to consider aspects other than economic ones, such as product quality or environmental sustainability. For all of these reasons, the need for more efficient and productive management systems in order to automate and optimize many strategic and operational decisions has increased over the last few years.

Among these decisions, it is possible to highlight the selection of the most suitable feeding strategy. These decisions are of greater importance not only because of the direct effect on the breeding costs they have, since feed is the main operational cost in in finfish aquaculture, but also because of they are the maximum responsible for the quality of the final product and the effect on the environment that surrounds the farm, two of the criteria most valued by stakeholders. Furthermore, feeding decisions have an added complexity: The existence of many different feeds and the possibility of combining them during the fattening process cause that traditional optimization techniques are not applicable to this problem or lead to computation times too long for practical purposes.

In order to address this problem, the present work integrates a multiple-criteria methodology with an evolutionary metaheuristic technique that allows determining the best sequence of feeds to be used throughout the fattening period, depending on multiple optimization objectives. In spite of their wide applicability and simplicity, metaheuristic techniques are not being used in the management of aquaculture farms as widely as in other contexts. In particular, genetic algorithms are well suited to address complex problems that arise in the management of such farms. In this regard, this work states a model in which the preferences of the decision maker are included thanks to the AHP methodology and these preferences influence the definition of the fitness function that a genetic algorithm subsequently uses.

In this regard, the main results of the simulations carried out seem to confirm the goodness of the model for the determination of feeding strategies in aquaculture farms that are affected by variations in environmental conditions. In addition, these results help to confirm that the combination of several commercial feeds in the same feeding strategy may improve the results obtained by one-feed strategies that considers only one commercial feed along all the production process.

In the context of the management of aquaculture companies, the implementation of the developed model allows multiple criteria to be introduced in the decision-making process, thereby enabling producers to find solutions suited to their needs from the many alternatives in very short time. All this is translated in a contribution to the improvement of the efficiency and flexibility of the decision-making processes, both regarding operative and strategic decisions.

From the point of view of the management of production processes, the proposed model allows to identify the feeding strategy that optimize the economic performance of the farm. However, and different from previous works that only considered the economic criteria in the decision process, this model also opens the door for aquaculture managers to find the feeding strategy that provides the best results in terms of environmental sustainability or product quality. Considering several criteria in the same decision is not a minor issue. As in other production activities, those criteria in aquaculture are very often opposed and, in most of the cases, their importance is based on the subjective perception attributed by each manager. In such way, this model integrates multiple-criteria decision making techniques and genetic algorithms applied to the decision-making process, thereby enabling producers to find solutions suited to their needs. The computational time is also a key aspect, since the model finds a near-optimal solution by simulating a vast number of alternatives in a very short period of time. All this is translated in a contribution to the improvement of the efficiency and flexibility of the decision-making processes in aquaculture production, both regarding strategic and operative decisions.

Lastly, it is mandatory to consider some limitations and future lines of research as, for example, the incorporation of elements of fuzzy logic to introduce into the model the vagueness of any subjective judgment and the increase of the number of cages that would allow producers to make long-term planning in major aquaculture farms. This points to the need for more research studies on this line and sets out the future direction of them.

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# Capítulo 4

## *Aquaculture production optimization in multi-cage farms subject to commercial and operational constraints.*

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# Aquaculture production optimisation in multi-cage farms subject to commercial and operational constraints

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## Abstract

The new advances in production methods have led to an increase in aquaculture production to the extent that the industry can now aid traditional fishing in meeting the growing global demand for fish with the context of the depletion of fisheries' resources. In this new context, market competition has increased and the complexity of managing industrial-scale production processes involving biological systems is still a growing problem. This has also led, in many cases, to a lack of management capacity that increases when it comes to setting long-term strategic plans. This study presents a methodology that aims to help aquaculture managers in decision making. It integrates a multi-criteria model and a Particle Swarm Optimization (PSO) technique in order to provide a production strategy that optimizes the value of multiple objectives at a fish farm with multiple cages, batches, feeding alternatives and products. This multi-criteria approach takes into account not only the effect of biological performance on economic profitability, but also the effect on environmental sustainability and aspects of product quality. In addition, it enables consideration of new operational and commercial constraints, such as the maximum volume of fish harvested per week, based on labour and marketing constraints, or the minimum necessary volume of fish harvested on specific dates to comply with commercial agreements. Results obtained demonstrate the utility of this novel approach to decision-making optimization in aquaculture both when establishing overall strategic planning and when adopting new ways of producing.

## Keywords

Aquaculture management, Biosystems, Multi-criteria modelling, decision-making processes, Particle Swarm Optimization.

## Resumen en español

El desarrollo experimentado por los procesos productivos de la industria acuícola a lo largo de los últimos años no ha sido suficiente para dar respuesta totalmente a la complejidad existente a la hora de gestionar su actividad a escala industrial. Por este motivo, algunas industrias, como la de producción de dorada y lubina, siguen sufriendo algunos de los problemas tradicionales del sector, como la baja eficiencia y rentabilidad de sus procesos productivos o la gran volatilidad de sus resultados. Además, hay que tener en cuenta que el nuevo contexto global expone a este sector a nuevos desafíos provocados por unos métodos de producción más complejos, cambios en los patrones de consumo de pescado y la internacionalización de los mercados.

Este incremento de la complejidad de las empresas no es específico de la acuicultura, sino general en todos los sectores. Por este motivo, la investigación operativa ha evolucionado mucho a lo largo de los últimos años, proporcionando a los productores sistemas de gestión, para afrontar el día a día de las empresas, y sistemas de apoyo a la toma de decisiones, para llevar a cabo su planificación estratégica. Estas herramientas, a pesar de su complejidad técnica, prestan especial atención a potenciar su usabilidad para permitir a los gestores, sin especial formación técnica, utilizarlos de forma eficaz en sus empresas. En este sentido, la industria acuícola podría dar respuestas a algunas de sus necesidades fundamentales, como es la aplicación de estas metodologías a granjas de mayor tamaño, las cuales toman decisiones para múltiples unidades productivas (jaulas) de forma sincronizada, teniendo en cuenta las restricciones operativas y comerciales de la empresa y la situación del mercado.

Por todas las razones anteriores, el objetivo central de este artículo ha sido abordar la optimización del proceso de toma de decisiones de forma completa, es decir, integrando las principales decisiones como parte de un proceso conjunto a largo plazo que considere la existencia de múltiples jaulas y lotes, manteniendo el enfoque multicriterio.

### Metodología

Con este fin, este artículo propone una innovadora metodología que permite optimizar las principales decisiones de producción en acuicultura (fecha de siembra, especie y peso de los alevines utilizados, estrategia de alimentación y fecha de despesque) en contextos complejos en los que se dispone de más de una jaula (multijaula), un horizonte temporal de varios años (multilote) y diferentes limitaciones a la actividad.

Para ello, se ha utilizado una técnica de optimización de enjambre de partículas (PSO) que permite abordar en un tiempo de computación adecuado el proceso de búsqueda de una estrategia de producción óptima, utilizando el valor conseguido por cada alternativa en la función objetivo multicriterio desarrollada en los artículos anteriores. Además, se ha incluido la posibilidad de introducir restricciones operativas y comerciales, con el objetivo de incorporar los objetivos de producción máximos y mínimos de las empresas.

Resultados

Los resultados obtenidos por esta metodología en diferentes escenarios han demostrado la utilidad de este enfoque novedoso para la optimización de la toma de decisiones en la acuicultura. A este respecto, el método de optimización desarrollado en el presente trabajo permite a las empresas superar algunas de las mayores limitaciones y lagunas específicas de la acuicultura, como la integración de varias jaulas y en la planificación estratégica a largo plazo. De esta forma, se aborda directamente uno de los desafíos clave en la acuicultura en los últimos años, la posibilidad de mejorar la eficiencia de sus procesos productivos para minimizar el uso de recursos y maximizar las ganancias.

Además, la decisión de considerar las restricciones operativas y comerciales ha demostrado ser clave, no solo porque la existencia de restricciones laborales y físicas es inevitable en este sector, sino también por el gran impacto que los acuerdos comerciales han tenido en la planificación de la producción. Estos acuerdos representan una reducción en la incertidumbre en torno a las ventas de la compañía, lo cual es muy importante en un sector de riesgo como la acuicultura, pero, al mismo tiempo, aumenta la complejidad de la gestión debido a la dificultad que supone incorporarlos a la planificación.

Por todo esto, este artículo proporciona evidencias empíricas sobre la capacidad de las técnicas metaheurísticas de optimización para mejorar los resultados de las empresas, tanto en problemas tradicionales de objetivos múltiples, como en problemas complejos de optimización con restricciones.

## 4.1. Introduction

Over the last few decades, major developments in the new information and communication technologies (ICT) has allowed producers to greatly improve their management capacity in the vast majority of productive sectors, as well as in primary industries. This has led managerial decisions to rely more than ever on large volumes of verifiable data, and to use expert systems capable of integrating such large volumes of data in order to optimize processes and generate useful outputs to help decision-makers. In this way, thanks to the rolling out of the so-called data-driven decision management, the productivity and the market value of many companies has increased significantly, as shown in the study conducted by Brynjolfsson, Hitt and Kim (2011).

During this time, aquaculture production has become a fast-growing food production industry as a result of advances in new intensive production methods. However, operation research techniques to support farm management have not been developed to the expected extent in a new and expanding industry that is highly dependent on biological and environmental factors. In this regard, the interest in bio-economic models that simulate the cultivation process has increased lately (Llorente and Luna, 2016), but aquaculture management has yet to see sufficient development of techniques to better understand and optimize decision-making processes. This problem has become even more serious in recent years for the reason that the few simulation models and optimization techniques that have traditionally been applied are no longer adequate to efficiently collect and handle the large volumes of biological data and the increasing number of factors involved in this activity.

In terms of the complexity of aquaculture production processes, major research efforts have been made over the past 30 years focused on understanding biological aspects or looking for empirical relationships in the fattening process. However, most studies do not allow managers to go beyond default bio-economic models, based on the effects of water temperature or feed ration (Seginer, 2016), in order to consider the new objectives which are in ever increasing demand by stakeholders as, for example, the environmental sustainability. In this respect, multi-criteria decision-making (MCDM) techniques have been successfully applied in many sectors for integrating various objectives (Ishizaka & Labib, 2011), even when decisions have to be made in the presence of subjective criteria which usually enter into conflict, as is the case of aquaculture (Tzeng & Huang, 2011). However, several review papers, from those developed by Mardle and Pascoe (1999) to Mathisen, Haro, Hanssen, Björk and Walderhaug (2016), have highlighted the few publications on multi-criteria decision-making within this sector compared to other fields. Moreover, in those cases in which this approach has already been applied, it only addresses specific problems, such as site selection (Dapueto et al., 2015; Shih, 2017) or feed selection (Luna, Llorente, Cobo, 2019a, 2019b).

In addition, the process of feeding fish is increasingly carried out in large facilities, with many production units (cages) that are at different stages of their product life cycle. This has improved the possibilities and efficiency of the sector, but at the same time has increased its market competitiveness and management complexity when it comes to setting a long-term strategic plan. In this regard, different management tools and Decision Support Systems (DSS) have addressed this problem, providing expert information in an easy-to-use manner to end users. However, as stated by Cobo, Llorente, Luna and Luna (2018), there is a need to consider their application to large farms, with more than one production unit as well as several supply agreements with large retailers that demand a continuous supply of produce throughout the year. Accordingly, these methodologies or systems have to be capable of sequencing seeding and harvesting decisions among multiple production units and cultivation cycles, considering different constraints in order to be practically applicable to help producers when establishing an optimal strategic plan.

For all the above reasons, the central goal of this paper is to provide aquaculture producers with a model to address their decision-making throughout the entire on-growing process, which would lead to more efficient management of both small and large aquaculture companies. The achievement of this objective required first the implementation of a multi-criteria model that enables consideration of the effect of the biological performance of a farm on three crucial objectives: its profitability, the environmental sustainability, and the quality of its final product. Secondly, it also entails the optimization of the operational and strategic decision-making process of a company with multiple cages, cycles, feedstuffs and fish products. In addition, this optimization process also takes into account operational and commercial constraints, i.e. the maximum amount that the company's workers could harvest per day or the maximum selling volume for the company at the market price, making the challenge even tougher.

With this aim, a population-based stochastic optimization technique inspired by the social behaviour of groups of animals, namely Particle Swarm Optimization (PSO), has been used to conduct the process of finding the optimal production strategy. This method is focused on improving the performance of multiple objectives with a low computational cost by synchronizing seeding and harvesting decisions and the feed and fingerlings selection. Regarding aquaculture management, although PSO has been successfully applied to solve many multi-objective problems in other sectors (de Campos, 2019), there have only been a few applications of it and they have a single economic aim, such as those by Yu and Leung (2005, 2009) and Cobo, Llorente and Luna (2015).

Therefore, this study constitutes a novel contribution to the existing state of the art of data-driven approaches to fish farming, integrating a MCDM model and an Artificial Intelligence (AI) metaheuristic technique, PSO. In this regard, one of the most promising aspects is the possibility of taking advantage of advances in information technologies both to understand and model the different processes involved in aquaculture and to improve management processes which enhances operational efficiency. This would make it possible to carry out the short and long-term operational and strategic planning more efficiently at aquaculture facilities with a large number of floating sea cages, which is very important since each fingerling has to be fattened for about one year to reach the minimum commercial weight.

The rest of the paper is structured as follows. First, section 2 explains the methodology we have developed, while Section 3 elucidates the model. Then, the model is tested in Section 4 for the case of gilthead seabream farming under three scenarios of commercial and operational constraints. To conclude, section 5 discusses the developed methodology and the potential implications of the results.

## 4.2. Simulation and optimization methodology

This section presents the work carried out to develop a new simulation and optimization methodology with the aim of addressing the current operational and strategic problems of aquaculture producers. With this aim, it explains the multi-criteria model used, defines the metaheuristic optimization technique developed to address the complex problem of finding a near optimal strategy with an acceptable computational cost and outlines the data collection process carried out.

In this regard, although these methods could be applied to the cultivation of the vast majority of aquaculture species, the present study started by addressing the entire fattening process of gilthead seabream (Sparus aurata) and European seabass (Dicentrarchus labrax). The selection of these species was the result of a comprehensive analysis of the industry, in which the process of breeding these species is relatively recent, but has undergone rapid growth over the last few years. This means that unlike other species such as salmon, the process of cultivating these fish faces more problems of profitability and difficulties in reducing production costs, mainly due to the existence of many small companies and the overwhelming influence of external factors (Llorente & Luna, 2013).

Regarding the focus on the operational strategic planning of aquaculture farms of the present work, each cage at the farm will have an individual strategy that consists of several cultivation cycles (batches), with the assumption that a batch cannot be stocked until the previous one has been harvested, but will also be synchronized by their respective seeding date (Sd) and harvesting date (Hd) with all the others. This aim also includes the selection of the product (Pt) the farmer wishes to sell between seabream and seabass, the initial weight of the fish fingerlings (Fw) and the feeding decision (F). The overall company profits are subsequently estimated from the results for each cage. Moreover, it is also essential to first test the validity of the entire strategic plan in terms of the farm's operational and commercial capacity, represented as a range in which the maximum volume of harvested fish per week (based on labour and marketing constraints) and the minimum volume of fish sold on specific dates (in order to comply with the commercial agreements that the producer has with recurrent buyers) are established.

In addition to this explanation, in order to facilitate understanding of the methodology developed, section 3 will elucidate the model.

### 4.2.1 Multi-Criteria model

The methodology developed in this work integrates a multi-criteria simulation model that allows aquaculture systems to estimate the value of the main criteria that lead decision-makers to select the right strategy for their company. In order to incorporate all these criteria in which the decision-makers could be interested in, a MCDM methodology was used. The application of this MCDM methodology begins with the Analytic Hierarchy Process (AHP) (Saaty, 1980), which allows the producers to rank the criteria according to their preferences or relative importance. AHP makes the process far easier since it makes it possible to compare the criteria by pairs, forming a matrix that facilitates the integration of different subjective measures into a final weight for each criterion, turning human judgements into exact or fuzzy numbers (Chan & Kumar, 2007).

Subsequently, as simultaneously optimizing all the criteria is impossible, the objective function to maximize, F(X), is built using the Technique of Order Preference by Similarity to Ideal Solution (TOPSIS). First developed by Hwang and Yoon (1981), this technique estimates the relative closeness of each alternative to two theoretical and opposed ideal solutions for the company based on the relative importance of the criteria, where $d^{-}(X)$ and $d^{+}(X)$ represents the separation of criteria values of *X* from the negative ideal and the positive ideal solution respectively. This integrates the simulation of the results of all the criteria in a unique fitness function that enables the system to compare and rank the different alternatives when looking for an optimal strategy.

$$F(X) = \frac{d^{-}(X)}{d^{-}(X) + d^{+}(X)} \tag{1}$$

In practice, the producer could adapt this method to a specific selection of important criteria or choose from a predetermined list. In the present case, given the current consumers and producers' demands, the multi-criteria model is formed by three different submodels that estimate the economic, environmental and product quality performance of a farm with the support of a biological model that simulates the biological processes of the farm on which everything else depends. To do this, based on previous work by Luna et al. (2019a), the following criteria have been selected within each submodel to represent the most important aspects to consider (Fig. 1).

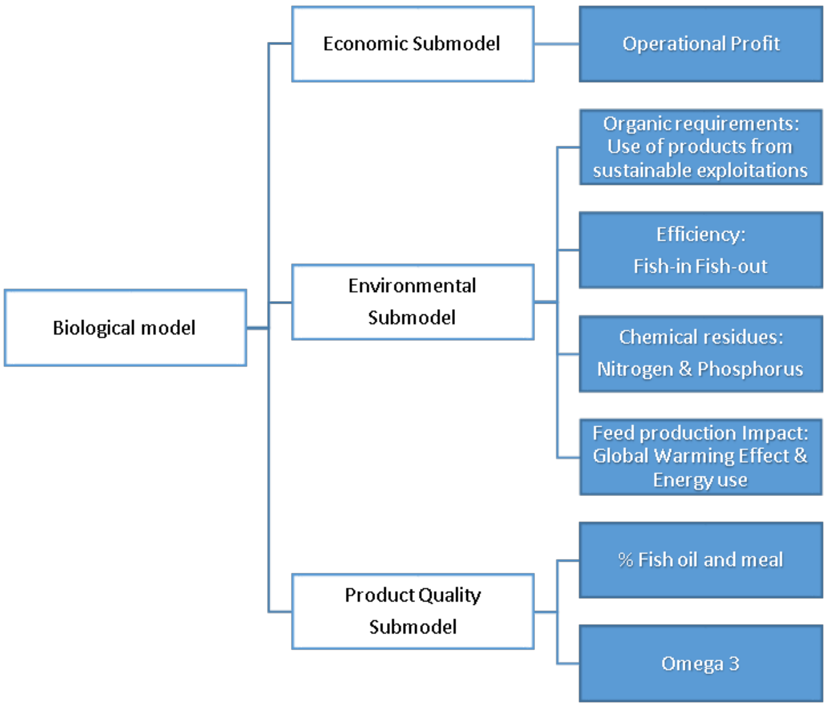


Fig. 1 Hierarchical structure of the decision criteria included in the multi-criteria model.

#### 4.2.1.1 Biological model

The biological model simulates the fattening process of each fish batch, which depends on growth, feeding and mortality rates for the selected production strategy. In this case, it depends on the seeding date (Sd), selected fish fingerlings (Fw), feed employed (F) and harvesting date (Hd).

Our model is based on the bio-economic model described in the study of Llorente and Luna (2014), so it follows the principles of fish physiology consist of seeding, fattening and mortality, as first considered in a model of the growth of salmonids (Stauffer, 1973). In this way, the value of the growth and feeding rates depends on three essential factors, the water temperature, which is directly influenced by the seeding and harvesting dates; the diet quality, which depends on the selected feed; and the individual fish weight, which evolves over time from the initial fingerling weight, as has been proven in different studies (Hernández, León-Santana, León, 2007; Seginer, 2016). In addition, the number of fingerlings released is calculated to obtain the maximum biomass density at harvesting time, taking into account the natural mortality and the average weight at harvesting time. It is also assumed that all the cages of a farm are exposed to the same environmental conditions.

However, it goes one step further, not only because it considers multiple optimization criteria, but also because it starts out from the following new assumptions that advances the modelling of these processes in aquaculture:

- First, the present study has advanced the practical applicability of these models to aquaculture farming, as it allows multiple cages and production cycles to be considered. This is crucial due to the existing trend in aquaculture of carrying out the fattening process in large facilities with the aim of exploiting economies of scale. Furthermore, it enables producers to adapt other decisions, such as the feeding strategy, to the company's overall strategy.
- In this case both alternatives are allowed; the traditional utilization of the growth, and feeding rates provided by feed suppliers or the use of specific functions based on empirical findings on those two variables for each farm according to different aspects. In any case, it must be noted that the model assumes that there is a range of abiotic factors (temperature, light, salinity and oxygen) which the producer cannot influence in an economically efficient way (Brett, 1979) due to the fact that the process is carried out in sea cages. On the contrary, an excess on the cage's total biomass could change how the abiotic factors affect the fish and, therefore, the mortality rates. For this reason, it is assumed that producers will keep the maximum biomass below the maximum

insurable biomass density (20 kg $m^{-3}$), or at the maximum density allowed in the case of ecolabelled production (15 kg $m^{-3}$), so that the main rates are unaffected (Luna, 2002).

- Lastly, while other methodologies assume that there are no constraints that may affect the overall seeding and harvesting of the cages, the one developed here assumes the presence of operational and commercial constraints. In the vast majority of cases, all the fish in a cage cannot be harvested at the same time due to labour, physical or commercial constraints; i.e. all the fish from a farm cannot be harvested and sold at the same time. With regard to the seeding date, it is assumed that the offer of fingerlings remains unchanged throughout the year (Gates & Mueller, 1975).

Starting out from those assumptions, the biological model is able to simulate the final growth, feeding and mortality values for each strategy. As explained in section 3, based on some values, such as the total amount of feed used throughout the process or the total biomass of fish, the developed model can estimate the results for the following submodels in order to approximate the farm's economic, environmental and product quality performance.

4.2.1.2 Economic submodel

Although the traditional approach, in which only economic results mattered when designing the aquaculture production strategy, no longer prevails in many cases, the economic performance is still a crucial aspect for the long-term sustainability of a company. In this sense, marine aquaculture presents good production times but profitability varies depending on the decisions taken and a number of external factors.

In the case in hand, the economic model focuses on the maximization of the operational profitability of the farm. This is obtained by subtracting the operating costs incurred in the fattening process from the income obtained from sales. With this aim, since most aquaculture producers sell their production to large intermediaries, company income is calculated by multiplying the total amount of fish harvested each week by the weekly average ex-farm price in USD per kg. This market price also depends on the commercial size of the fish and differs significantly between conventional and organic production. Hence, the obtained income will be directly influenced not only by the overall growth achieved, but also by the selected feeding and production strategies (feed stuff, harvesting dates...)

Reducing operating costs is the most influential way of increasing the company profit. In this case, only variable costs, such as fingerlings and feeding costs, are taken into account, as the remaining costs are not directly influenced by the selected strategy and can be assigned using an allocation key. In particular, feeding costs are the main operating costs in finfish aquaculture and can account for 30-60% of total operating costs, most times depending on the protein content (Goddard, 1996; Hassan, Umar, Atiku, 2007).

#### 4.2.1.3 Environmental submodel

The environment is a very important variable in aquaculture, even more so in production processes carried out in sea cages. On the one hand, the biological model analyses how environmental conditions, which cannot be manipulated by the decision maker, affect system performance and should hence be taken into account to make a reliable decision (Casini, Mocenni, Paoletti, Pranzo, 2015). However, the effect of the actions carried out throughout the production process on the environment in general and on the surrounding environment in particular is even more important nowadays, hence the need to integrate an environmental submodel.

For this reason, the environmental submodel has been divided into 4 different parts that simulate the effect of each of the decisions taken throughout the production process in terms of environmental sustainability:

- Organic production requirements: The origin of the products used as part of the feeding process is one of the main criteria taken into account by regulators. In this regard, if the producer wishes to apply for an EU Ecolabel, the regulation No. 889/2008 of the European Commission (5 September 2008) establishes that feedstuffs shall be fully sourced by-products from organic aquaculture or fisheries certified as sustainable in order to reduce the effect on the environment. Therefore, it has been included as a key criterion in the model.
- Efficiency: This is one of the key aspects to reach a sustainable production in any industry. In this way, the Fish-in Fish-out ratio is a common way to measure the amount (kg) of fish needed to produce one kg of farmed fish to help make fish production more sustainable (Tacon and Metian 2008).
- Chemical Residues: In the same way, in order to minimize the environmental impact of aquaculture, stakeholders place the highest value on the prevention of chemical residues on antibiotic dispersion in the natural environment, such as nitrogen and phosphorus waste (Lembo, Jokumsen, Spedicato, Facchini, Bitetto, 2018).

Feed production impact: Feed fabrication and transport consume the majority of the energetic input and produce the majority of emissions to the point that it could lead more concerned producers to select a different feed. In this regard, the global warming potential impact ($CO_2$ equiv.) and the energy use (MJ equiv.) criteria are usually considered. Data may be either provided by each feed producer or estimated depending the feed ingredients, since there are empirical studies on the impact of the utilization of certain raw materials when producing feedstuff, such as the work conducted by Pelletier and Tyedmers (2007)

4.2.1.4 Product quality submodel

The quality of the fish, perceived via their organoleptic characteristics, is directly influenced by many variables ranging from feeding strategies to genetic and environmental factors, including salinity, current and temperature (Rasmussen, 2001; Cordier, Brichon, Weber, Zwingelstein, 2002). Furthermore, many of these organoleptic characteristics are difficult to measure and objective way since different costumers and markets could present different assessments or preferences.

However, the most common representative factor of fish quality is the amount of fatty acids from fatty fish consumed by the farmed fish. In this regard, Shahidi and Alasalvar (2010) refer to the amount of omega-3 fatty acids throughout the entire growth process to optimize fish quality. Otherwise, some studies have shown that it is sufficient for the fish to be fed during the last 90 days with diets containing fish meal and oil to almost fully restore initial fatty acids in their muscles (Grigorakis, 2010).

Hence, the multi-criteria model includes two criteria to maximize the perception of quality: the use of omega-3 and the fish meal and oil that the feed used during the last 90 days of each batch.

### 4.2.2 Particle swarm optimization process

Given the difficulties of finding an optimal strategy for the problem addressed in this study, namely the complex constraints and the large number of alternatives, classic optimization techniques are not applicable to it or lead to long computation times. Metaheuristic techniques, however, work better under these conditions as they sacrifice the guarantee of finding the optimal solution for the sake of getting good solutions in a significantly reduced amount of time (Blum and Roli, 2003).

Several metaheuristic techniques have been developed in recent years, many of which are inspired by natural processes, such as natural selection for Genetics Algorithms (GA) and swarm intelligence for Particle Swarm Optimizations (PSO). PSO is an iterative and stochastic process method that models social behaviour to guide swarms of particles towards the most promising regions of the search space (Eberhart

& Kennedy, 1995). As Cobo et al. (2018) stated, this method is especially useful in aquaculture problems like the one addressed in this paper, not only because of its advantage in terms of robustness and flexibility, but also due to its higher efficiency when used to solve nonlinear problems with continuous design variables (Hassan, Cohanim, de Weck, Venter, 2005).

In the present case, Particle Swarm Optimization is integrated with the multi-criteria methodology to optimize this complex real-world problem. As explained before the MCDM proposed methodology considers two hypothetical alternatives: the positive-ideal, with the best values for all the attributes, and the negative-ideal, with the worst values for all the attributes. The best alternative would be one that is closest to the positive-ideal solution and farthest from the negative-ideal solution. The relative closeness for each potential solution with respect to positive ideal solution can be used as fitness function in an optimization process based on an evolutionary approach. As the number of alternatives is infinite, for the estimation of positive-ideal and negative-ideal values, we proceed as follows. Firstly, a hypothetical solution must be generated for each feeding alternative using a heuristic approach and with the aim of exploiting the full potential of the farm. For example, assuming that the fattening process of each batch lasts for as much time as possible (the total number of weeks divided by the number of batches per cage). Then the best value for each criterion among the hypothetical solutions is selected and improved by a supplement of ±75%, assuming that the PSO can find an alternative with better results, but not improved by more than 75%.

Furthermore, the problem addressed in this study is sometimes subject to specific constraints. which greatly complicate the optimization process. In complex Constrained Optimization (CO) problems, the search space consists of two kinds of points: feasible points, where all the constraints are satisfied; and unfeasible points, where at least one of the constraints is not satisfied (Parsopoulos & Vrahatis, 2002a). In order to address this problem, PSO allows stationary and non-stationary penalty functions to be introduced, this solves the CO problem via a sequence of unconstrained optimization problems (Joines & Houck, 1994).

The PSO methodology developed in the present study follows the steps of the standard particle swarm algorithm initially developed by Eberhart and Kennedy (1995) with some variations to suit different needs of multi-criteria optimization:

1. It starts out by generating a population of random solutions that are distributed in a position, Xi(t), and moved through the hyperspace with a velocity, Vi(t).
2. Secondly, the result for each random solution is evaluated. In this case, the fitness function estimates the closeness of each alternative to the hypothetical ideal solutions.

3. A dynamically modified penalty is applied, deducting 1 from the fitness function of each particle for each non-satisfied constraint
4. At each time step, each particle changes its position due to three components that influence the velocity: the best solution it has achieved ($X_i^{pbest}$), the overall best value obtained ($X^{best}$), and an inertia constant ($w$).
5. The last three steps are repeated until the stopping criterion is met. In the present case, this criterion is the number of movements without any improvement in the fitness function.

Before starting this process, the proper functioning of the PSO algorithm involves choosing the following 5 configuration parameters: The number of particles or population size ($pop_{size}$) and the maximum number of iterations, usually set in line with the dimension and the perceived difficulty of the problem (Poli, Kennedy, Blackwell, 2007), and the acceleration coefficients, which are the inertial and the best social and personal positions reached. All these parameters exert a significant influence over the effectiveness of the PSO algorithm and were accordingly selected in a different way for each proposed scenario. The introduction of a methodology for dynamic or self-adaptive parameters could be another option that obviates this tedious pre-processing task of parameter fine-tuning (Montalvo, Izquierdo, Pérez-García, Herrera, 2010).

### 4.2.3 Test and calibration

New methods for fish farming need to be more advanced and smarter in the sense that the industry needs to shift from experience-driven to knowledge-driven approaches so as to better optimize production. With this aim, the new methodologies need to be rigorously tested in close cooperation with the different stakeholders. High quality data is also crucial, so companies are interested in gathering a greater quantity and variety of data than ever before.

In this regard, as a test of its practical application, the developed methodology has been applied to the decision-making process of a hypothetical gilthead seabream farm. The proposed objective was finding the strategic planning that optimizes the preferred criteria for a farm with 3 different cages of 200 m$^3$ over two production cycles (table 1).

Table 1. Production period and farm capacities in the case under examination

| Variables | Value |
|---|---|
| Starting Date | 17/06/2019 (Week 0) |
| End Date | 13/06/2021 (Week 104) |
| Number of cages | 3 |
| Cage capacity | 200 m$^3$ |

To this end, each cage at the farm adopts a synchronized strategy that consists of the seeding date, harvesting date, feeding alternative and selected fish fingerling, for all its cycles. However, the complexity of this optimization process is mainly marked by the search space size and the optimization constraints included. For this reason, three different scenarios have been tested, from a scenario with no constraints to the gradual introduction of the already defined operational and commercial ones:

- Firstly, the developed methodology was tested in a scenario without any operational or commercial constraints. This enables the proper functioning of the methodology to be tested in a situation in which every candidate solution within the search space constitutes a valid alternative. In this case, the global optimum could be found without depending on the feasibility of the solution.
- Then, the operational and commercial aspects affecting maximum volume of fish harvested per week have been taken into consideration. In this regard, this scenario includes both the existence of operational constraints when harvesting due to the labour capacity of farms and a commercial constraint to avoid the concentration of its selling activity in specific dates which would saturate the market and lower the selling prices. In order to consider these constraints, the model was modified to divide the harvesting process of each cage in four weeks and to fix a maximum amount of fish harvested of 4 tonnes per month, discarding solutions that entail the harvesting of two cages at the same time.
- Lastly, in addition to the aforementioned constraints, a minimum volume of harvested fish on specific dates has been set in order to comply with commercial commitments. Specifically, it is assumed that the farm agreed to sell 0.5 tonnes of gilthead seabream weighing around 300 g in the following four weeks: 30, 50, 70, 90. This would allow the company to obtain profits in a sustained manner throughout the year, but it also makes the problem much more complex.

On the other hand, the complexity of aquaculture processes makes it especially difficult to manually extract information from data of both external sources or the farm data, even more so when each farmer manages multiple units. However, technological advances over the last decades have enabled us to address this problem with the development of several methods, from online databases and ICT applications to collect and visualize key information (Piplani et al., 2015), to wireless sensors (Shi, Sreeram, Zhao, Duan, Jiang, 2018) or computer vision technologies (Zion, 2012) that, although are less developed, are capable of monitoring many variables, such as the fish number, size measurement, mass estimation, gender detection, quality inspection, species identification or behaviour control. Føre et al. (2018) introduced the Precision Fish Farming (PFF) concept which has the aim to improve the farmer's ability to monitor, control and document biological processes in fish farms.

Based on these technological advances, testing the developed methodology requires the use of a database that integrates all the information needed to set the strategic planning of an aquaculture farm. In this case, each decision variable is limited by the underlying assumptions and the information that was taken both from primary sources, such as oceanographic buoys and feed manufacturers, and to a lesser extent from secondary sources, namely other research studies or price databases. This information includes the following details:

- Feed information: In this case, three feedstuffs have been included as a representation of the different feeding alternatives within the feed market. The first feed (F1) represents a normal feed, with acceptable rates under normal circumstances and a very competitive price (1.11 USD kg). The second (F2) is a feed with an increased percentage of fish protein (38% versus the 25% of the first one), which means better growth rates even under unfavourable weather conditions but also a slightly higher price (1.19 USD kg). The third feed (F3) represents the choice of organic production, as it is a high quality (55% of fish protein) and high price (1.49 USD kg) feed made entirely with products from organic fisheries/productions. Other aspects and feed components are provided directly by feed producers, with the exception of the feed production criteria, which were estimated based on a secondary source, the study conducted by Pelletier and Tyedmers (2007). Information in feed components can be found in the study published by Luna et al. (2019a).
- Biological data: This methodology allows producers to make decisions regarding which type (weight and species) of fingerlings to seed, the seeding and harvesting weights and the feeding strategy. To this end, data on growth and feeding rates for each species is needed. This data usually depends on the three aspects, the selected feed, the water temperature and the fish weight. In the present case, in order to simulate the long-term results of a farm, the specific information on growth and feeding rates of Gilthead seabream directly provided by feed suppliers is assumed to be an adequate estimation. In this respect, table 2 shows a summary of the growth and feeding rates used, in a case were the feeding rate and fish weight were previously fixed.

Table 2. Daily feeding rate and expected growth for a fish of around 100g as a percentage of its mass.

| Temperature | Feeding Rate | Growth Rate Feed 1 | Growth Rate Feed 2 | Growth Rate Feed 3 |
|---|---|---|---|---|
| 16 | 1.0 | 0.39 | 0.44 | 0.46 |
| 18 | 1.1 | 0.53 | 0.57 | 0.59 |
| 20 | 1.3 | 0.71 | 0.72 | 0.82 |
| 22 | 1.4 | 0.86 | 0.88 | 1.00 |
| 24 | 1.5 | 0.97 | 0.99 | 1.13 |

- Economic data: Price is one of the most important criteria affecting the results of the farm. However, most aquaculture producers sell their production to large intermediaries and have no control of the ex-farm price, so they have to work in reducing the operational costs or select the best harvesting dates in order to improve their profitability. In the present case, fish selling prices has been collected from the main Spanish wholesale market prices for the commercial classes of seabream (300–400g, 400–600g, >600g) for 2018 on a weekly basis (Fig. 2), and used as a proxy of the ex-farm price applying a reduction comprising the average wholesale-producer margin, as stated by MAPAMA (2012). Furthermore, it should be noted that organic aquaculture presents a price premium. Based on the study carried out by Zander and Feucht (2017), which shows the costumer's willingness to pay varies between 7% and 20% depending on attribute and country, prices for organic products has been increased by 15%. Regarding the farm costs, these are estimated in each scenario depending the amount of feed used.

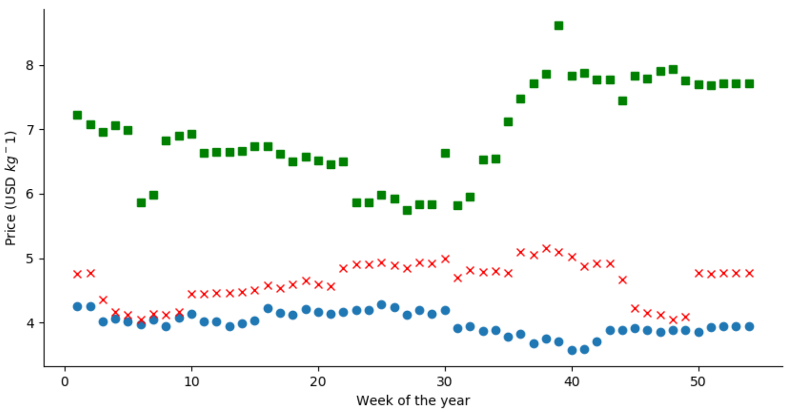


Fig. 2. Weekly average ex-farm prices in 2018 by mass category: under 400g (circles), between 400g and 600g (crosses) and above 600g (squares).

- Environmental conditions: From the very beginning and throughout the entire production process, many external factors directly influence the strategic plans in aquaculture. Most noteworthy is the water temperature, which is the objective of a large number of research studies, such as the one conducted by Besson et al. (2016), and is a main variable influencing growth and feeding rates in the biological model. For this reason, daily data of temperature, salinity and currents were obtained from the oceanographic buoys network of the Spanish Port Authority but only the last year's temperatures have been used as a proxy of future temperatures. Figure 3 shows the temperatures used for the simulation, corresponding to the buoy located close to Tarragona (latitude 41.02 and longitude 1.50), given that the Mediterranean Sea is the most common place to farm gilthead seabream.

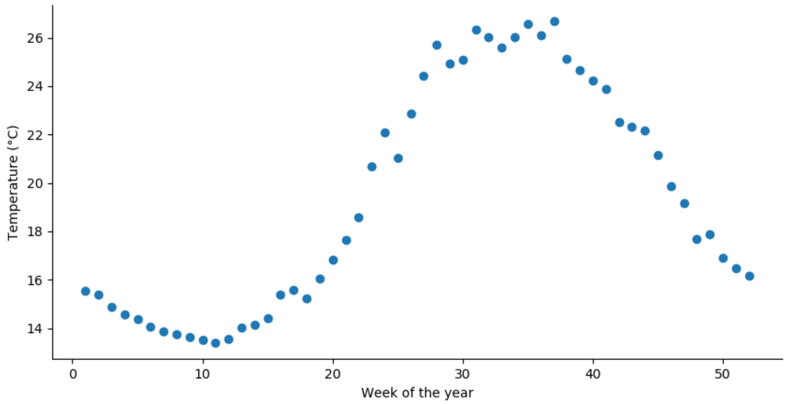


Fig. 3. Average weekly sea water temperature at the farm location measured in 2018 by the *Puertos del Estado* buoy network

- Producer preferences: the MCDM technique used in this work allows producers to compare the selected criteria by pairs in order to assign a specific importance (%) to each one depending on their preferences. As a result, Luna et al. (2019a) present, three common scenarios on aquaculture producers' preferences with respect to the importance of the criteria under study here. The present study incorporates an example of the point of view of a traditional producer, who affords more importance to the economic performance of the farm and, in a lesser extent, to the consumers' perceived product quality (table 3).

Table 3. Relative importance weights of each decision criterion for a theoretical producer especially concerned with the economic criteria.

| Criteria | Relative Importance |
|---|---|
| **Economic Criteria** | **81.8%** |
| Profit | 81.8% |
| **Environmental Criteria** | **9.1%** |
| % Organic Feed | 0.3% |
| Fish in-Fish out Ratio | 3.2% |
| Total Nitrogen | 1.0% |
| Total Phosphorus | 1,0% |
| Energy Use | 1.8% |
| Global Warming Potential | 1.8% |
| **Quality Criteria** | **9.1%** |
| % Fish origin feed | 0.9% |
| Omega-3 | 8.2% |

## 4.3. Model description

*Parameters:*

*N, M*: maximum number of cages and batches, respectively.

$Vol_c$: capacity ($m^3$) of cage $c \in \{1,2,\dots,N\}$

$Do_{max}, Ds_{max}$: maximum density of biomass in organic/standard production

$N_{weeks}$: time horizon (number of weeks)

$T_t$: estimated seawater temperature in week $t \in \{1,2,\dots,N_{weeks}\}$

$N_{prod}$: number of final products. Each product $P_k$ with $k \in \{1,2,\dots,N_{prod}\}$ is determined by a species, a type of production (organic/standard) and a minimum commercial size.

$N_{feeds}$: number of available feeds. Each feed $F_f$ with $f \in \{1,2,\dots,N_{feeds}\}$ has the following information: price, % from sustainable exploitation, residual nitrogen and phosphorus, estimation of the impact of feed production (energy use and global warming potential), % fish feed and contribution of omega-3.

*Functions:*

*M(s,w,T)*: fish mortality, which depends on the species, its size and water temperature

$p_f(s,w,pt)$: fingerling price, as a function of the species, weight and type of production.

$p_d(w,t,pt)$: sale price of the final product *d*, which depends on final weight, harvesting time and production type.

*feedQ(f,p)*: a Boolean function that determines whether feed $F_f$ is suitable for the production of product $P_p$.

$R_f(w, T_t)$: food ration of feed $F_f$, which depends on fish weight and water temperature.

$GR_f(w, T_t)$: growth rate of the fish using feed $F_f$, which depends on fish weight and water temperature.

*Decision variables:*

Overall production plan: $X = \left(P_{cage,batch}\right)_{\substack{cage=1,\dots,N \\ batch=1,\dots,M}} = \begin{pmatrix} P_{1,1} & \cdots & P_{1,m} \\ \vdots & \ddots & \vdots \\ P_{n,1} & \cdots & P_{n,m} \end{pmatrix}$

Planning the production of a batch from a cage:

$P_{cage,batch} = \left(Sd_{cage,batch}, Pt_{cage,batch}, Fw_{cage,batch}, F_{cage,batch}, Hd_{cage,batch}\right)$

where

$Sd_{cage,batch} \in \{1,2,\dots,N_{weeks}\}$: seeding date (week number from the initial week)

$Pt_{cage,batch} \in \{1,2,\dots,N_{prod}\}$: desired final product

$Fw_{cage,batch} \in [min_{weight}, max_{weight}]$: fingerling initial weight

$F_{cage,batch} \in \{1,2,\dots,N_{feeds}\}$: feed used for fattening.

$Hd_{cage,batch} \in \{1,2,\dots,N_{weeks}\}$: harvesting date (week number from the initial week, never before reaching the minimum commercial weight)

*Particle Swarm Optimization algorithm:*

$pop_{size}$: population size (number of particles)

$w \in [0,1]$: inertia component weight

$\alpha, \beta \in [0,1]$: social and personal best component weights

$X_i^k$ $and$ $V_i^k$ $with$ $1 = 1, \ldots, pop_{size}$ $and$ $k = 1, \ldots, iter_{max}$: position and velocity of particle *i* in iteration *k*.

$X^{best}$: global best position during the process, according to the fitness function

$X_i^{pbest}$: best position or particle *i* during the process, according to the fitness function

$V_i^k = wV_i^k + \alpha\, rand(0,1)\left(X^{best} - X_i^k\right) + \beta\, rand(0,1)(X_i^{pbest} - X_i^k)$: velocity vector for particle *i* in iteration *k*.

$X_i^{k+1} = X_i^k + V_i^k$: update of particle positions

*Fitness function (proximity to ideal solution):*

$C_j\left(X_i^k\right) \quad j = 1, \ldots, 9$: normalized values of the decision criteria in each particle

$d^+(X_i^k)$: distance from the positive ideal solution of criteria values of particle *i*.

$d^-(X_i^k)$: distance from the anti-ideal solution of criteria values of particle *i*.

$F\left(X_i^k\right) = \frac{d^-(X_i^k)}{d^-(X_i^k)+d^+(X_i^k)} - Penalty\left(X_i^k\right)$: relative closeness of particle with respect to ideal solution with a penalty if constraints are violated.

Objective: maximize the fitness function *F(X)*.

*Constraints:*

$minp(w) \leq Prod_w\left(X_i^k\right) \leq maxp(w)$ $with$ $w = 1, \ldots, N_{weeks}$: commercial or operational constraints for week *w*.

where

$Prod_w(X) = \sum_{cage=1}^{N} Harvest_X(cage, w)$: this represents the sum of amounts harvested in week *w* according to plan *X*.

## 4.4. Results

The simulation and optimization process takes place in three consecutive steps: first, the estimation of the objective function, based on the multi-criteria model; then the optimization parameters are selected in order to make the search process more robust and then the PSO methodology is used to find a near optimal strategy that maximizes the overall results of the farm in the three scenarios. The following sections show the result of each one and a summary of the main findings obtained.

### 4.4.1 Optimization objective

Every optimization technique advances towards an objective, which must be determined in the first place. When there is only one objective, this process is simple, but when multiple and opposing objectives have to be optimized things get a little more complicated.

In this case the objective is to help aquaculture companies to improve or optimize the results of their production processes regarding 9 different criteria. The use of a MCDM methodology helps in grouping them in a concrete objective function and, therefore, to overcome this problem. First it looks for an ideal value, which will never be reached, for each criterion and then that objective function measures the overall distance of the results of each alternative to these ideal values and ranks them by proximity/closeness. The work of the PSO methodology is as simple and complex as generating alternatives increasingly closer to that ideal.

With this aim in mind, this section shows three starting points or basic alternatives that were automatically generated only for the estimation of the ideal alternatives. As explained before, these are hypothetical solutions in which decisions are made without any sophisticated model, so they are identical for each cage, i.e. the seeding and harvesting dates for each batch are placed as far away as possible from each other, with the exception that one different feed is selected in each one of them. In this case, since there are two batches for each cage and the time horizon is equal to two years out, in each cage the fattening process is carried out twice. Then, the biological model estimates the achieved growth and the amount of feed used on a daily basis and the three submodels assess the value of each criterion from this data. Moreover, these results will also act as a benchmark for the analysis of the improvements obtained with the utilization of the methodology developed.

Once the results are estimated for the basic alternatives, the best value of each criterion is selected and improved by a supplement of ±75%, depending our intention of minimizing or maximizing its value, with the goal to generate those ideal solutions that will never be reached (table 4).

Table 4. Initial alternative strategies and hypothetical positive (negative) ideal optimization objective assuming a 75% improvement (worsening) in the combined use of feed versus the use of a single feed.

| | Obj | Alternative 1 | Alternative 2 | Alternative 3 | Positive Ideal | Negative ideal |
|---|---|---|---|---|---|---|
| Feed | | F1 | F2 | F3 | - | - |
| **Economic Criteria** | | | | | | |
| Profit (USD) | Max | 35,566 | 35,231 | 30,345 | **62,242** | **7,586** |
| **Environmental Criteria** | | | | | | |
| Organic Feed (%) | Max | 0 | 0 | 100 | **100** | **0** |
| Fish in-Fish out Ratio | Min | 0.65 | 0.95 | 1.25 | **0.16** | **2.18** |
| Total N (t) | Min | 3.87 | 3.76 | 3.42 | **0.85** | **6.77** |
| Total P (t) | Min | 0.81 | 0.86 | 0.60 | **0.15** | **1.50** |
| Energy Use (MJ equiv.) | Min | $4.85\ 10^8$ | $2.41\ 10^8$ | $4.29\ 10^8$ | **$6.03\ 10^7$** | **$8.50\ 10^8$** |
| Global Warming (kg $CO_2$ equiv.) | Min | $4.16\ 10^7$ | $2.04\ 10^7$ | $2.95\ 10^7$ | **$5.12\ 10^6$** | **$7.28\ 10^7$** |
| **Product Quality Criteria** | | | | | | |
| Fish origin feed (%) | Max | 25 | 38 | 55 | **96** | **6.25** |
| Omega-3 (%) | Max | 1 | 1 | 2 | **3.50** | **0.25** |

Special attention should be drawn to the fact that the multi-criteria model stands out as the most important part of the methodology, as both the initial step of estimating the results in order to generate the optimization objective and the evaluation of each alternative found by each particle of the PSO involves the use of the model.

### 4.4.2 Selection of the appropriate optimization parameters

The inclusion of multiple and complex constraints increases the complexity that the optimization methodology has to face and hence the computational cost of the entire process. Therefore, prior to starting the search process, the penalty function and the appropriate PSO components should be chosen in order to increase the efficiency of this search. To ensure the robustness of this methodology, each of the following options were tested in 100 different executions.

Firstly, with the aim of avoiding the loss of optimization capacity in complex scenarios, the decision about the penalty function that ensures compliance with the constraints should be taken. Penalty values can be fixed throughout the use of a stationary penalty function or dynamically modified one (non-stationary), although results obtained using the latter are almost always superior (Parsopoulos & Vrahatis, 2002a). In order to choose the best possible solution to this problem, three alternatives have been compared with the use of 90 particles and a maximum number of iterations of 30 in the more complex scenario, the third one:

- A strategy in which the closeness of every candidate solution that does not meet all the constraints are automatically changed to 0.
- A stationary penalty function that subtracts one (-1) from the closeness of any constraint which is not met.
- A strategy in which the penalty is dynamically modified, subtracting one (-1) from each violated constraint.

As can be seen in the table 5, the third penalization strategy proved to be the best alternative in this case.

Table 5. Comparison of the effect of using different penalty strategies on the performance of the algorithm.

| Method | Best Solution | Mean Solution | % of cases it founds a feasible solution |
|---|---|---|---|
| Closeness 0 | 0.36 | 0.16 | 60% |
| Fixed -1 | 0.51 | 0.25 | 60% |
| Dynamic | 0.59 | 0.43 | 90% |

In addition to the above and with the same aim, an appropriate combination of the five PSO parameters stands out as one of the crucial decisions. In this respect, there is an initial need to choose between two options regarding these parameters: solving the most complex problems by having a large population of particles, or moving the particles around in the search-space more times. In the case at hand, starting out from a larger population of particles allows the methodology to cover more search-space right from the beginning, which is very useful to find the few areas with feasible solutions.

In this regard, while fixing the number of particles to 90 was found to be sufficient to always find a feasible solution in the first two scenarios, the third one required the use of 120 particles to address such a complex constrained problem, as can be seen in table 6.

Table 6. Effect of variation in the number of swarm particles on the performance of the algorithm.

| Particles | Best Solution | Mean Solution | % of cases it founds a feasible solution |
|---|---|---|---|
| 60 | 0.41 | 0.20 | 50% |
| 90 | 0.59 | 0.43 | 90% |
| 120 | 0.67 | 0.55 | 100% |

Regarding the social and cognitive components, they start from an initial value of 0.2 and 0.8, but the first one is increased and the second reduced by 10% after each step to promote the exploration of the search space first and exploit the feasible areas after some steps.

### 4.4.3 Performance of the developed methodology

In order to measure the performance of the developed methodology in the different scenarios, it is necessary to observe two different aspects: how it meets the constraints and the effects on the company results.

Regarding the strategies found in order to meet the requirements (table 7), the closeness shown in the table refers to the proximity of each strategy to the ideal solution. It enables the comparison of the strategies found in each scenario and the analysis of how the inclusion of different constraints could force the methodology to discard the best strategies.

Firstly, when no constraints force the different cages to adapt to each other, all the three cages tend to choose practically the same strategy, which means that the harvesting processes are carried out in the same dates and it makes the same feeding decisions for the fingerlings. As an exception, it is possible to see small differences in some points that would undoubtedly be solved with more computing time. Anyway, closeness found is the highest and it is possible to assume that this strategy is near-optimal. This suggests the proper functioning of the methodology right from the start, at least in unconstrained problems.

In the second scenario, the introduction of constraints on the maximum amount of fish harvested forced the methodology to find a strategy that made different harvesting decisions. As shown in the table 7, in no case are two cages harvested at the same time even if we consider that now the harvesting process is divided into 4 weeks (the week specified and the following 3 weeks). As expected, this has led to a decrease in the closeness to the ideal alternatives, since it is moving away from the optimal weeks.

Lastly, in the third scenario, in addition to the aforementioned constraints, there are also constraints in the minimum amount of fish harvested on specific dates. This simulated a commercial agreement for selling 0.5 tonnes of gilthead seabream weighing around 300 g in the following four weeks: 30, 50, 70, 90. For that reason, there are a vast majority of regions of the search space where the constraints are not met, thus making it even more difficult to find a feasible solution first and then to move forward to a near-optimal one.

This approach has advantages and disadvantages. The main disadvantage is that best solutions do not satisfy the constraints so the closeness of the selected strategy is lower. However, alongside that, the solution found reflects more realistically the actual decisions of fish farmers, who carry out the selling process in a more distributed way in order to satisfy the commercial agreements but also to reduce some risk, such as the market risk.

Table 7. Summary of the best strategy found by the optimization methodology in each scenario.

| | | Scenario 1 | | | Scenario 2 | | | Scenario 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Results | Cage 1 | Cage 2 | Cage 3 | Cage 1 | Cage 2 | Cage 3 | Cage 1 | Cage 2 | Cage 3 |
| **Batch 1** | Seeding week | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| | Harvesting week | 39 | 35 | 35 | 35 | 39 | 44 | 28 | 37 | 47 |
| | Feed | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F2 |
| | Fingerling mass (g) | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| **Batch 2** | Seeding week | 44 | 38 | 38 | 39 | 43 | 51 | 31 | 44 | 50 |
| | Harvesting week | 82 | 82 | 82 | 82 | 90 | 96 | 70 | 87 | 99 |
| | Feed | F2 | F2 | F2 | F2 | F2 | F2 | F3 | F2 | F2 |
| | Fingerling mass (g) | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | Closeness [a] | 0.76 | | | 0.72 | | | 0.67 | | |

[a] The closeness measures the distance of each alternative to the hypothetical ideal solutions on a scale of 0 to 1, where greater is better.

Table 8 shows how a different harvesting strategy was found in each of the verification scenarios described above and the total amount of fish harvested each week. The third scenario in particular is worth highlighting, in which four mandatory points of sale are established, forcing the displacement of the optimal points.

On the other hand, company results are analysed not only by the economic profitability reached, but also by the environmental and product quality performance of the farm, as shown in table 9.

Table 8. Fish harvested (t) per week in three increasingly complex scenarios*

| Week | Scenario 1 | | | Scenario 2 | | | Scenario 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cage 1 | Cage 2 | Cage 3 | Cage 1 | Cage 2 | Cage 3 | Cage 1 | Cage 2 | Cage 3 |
| 28 | | | | | | | 0.60 | | |
| 29 | | | | | | | 0.60 | | |
| 30 | | | | | | | 0.60 | | |
| 31 | | | | | | | 0.60 | | |
| 32 | | | | | | | | | |
| 34 | | | | | | | | | |
| 35 | | 2.57 | 2.46 | 0.61 | | | | | |
| 36 | | | | 0.61 | | | | | |
| 37 | | | | 0.61 | | | | 0.65 | |
| 38 | | | | 0.61 | | | | 0.65 | |
| 39 | 2.51 | | | | 0.62 | | | 0.65 | |
| 40 | | | | | 0.62 | | | 0.65 | |
| 41 | | | | | 0.62 | | | | |
| 42 | | | | | 0.62 | | | | |
| 43 | | | | | | | | | |
| 44 | | | | | | 0.67 | | | |
| 45 | | | | | | 0.67 | | | |
| 46 | | | | | | 0.67 | | | |
| 47 | | | | | | 0.67 | | | 0.95 |
| 48 | | | | | | | | | 0.95 |
| 49 | | | | | | | | | 0.95 |
| 50 | | | | | | | | | 0.95 |
| 51 | | | | | | | | | |
| 69 | | | | | | | | | |
| 70 | | | | | | | 0.58 | | |
| 71 | | | | | | | 0.58 | | |
| 72 | | | | | | | 0.58 | | |
| 73 | | | | | | | 0.58 | | |
| 74 | | | | | | | | | |
| 81 | | | | | | | | | |
| 82 | 4.04 | 4.12 | 4.12 | 1.03 | | | | | |
| 83 | | | | 1.03 | | | | | |
| 84 | | | | 1.03 | | | | | |
| 85 | | | | 1.03 | | | | | |
| 86 | | | | | | | | | |
| 87 | | | | | | | | 1.05 | |
| 88 | | | | | | | | 1.05 | |
| 89 | | | | | | | | 1.05 | |
| 90 | | | | | 1.06 | | | 1.05 | |
| 91 | | | | | 1.06 | | | | |
| 92 | | | | | 1.06 | | | | |
| 93 | | | | | 1.06 | | | | |
| 94 | | | | | | | | | |
| 95 | | | | | | | | | |
| 96 | | | | | | 0.93 | | | |
| 97 | | | | | | 0.93 | | | |
| 98 | | | | | | 0.93 | | | |
| 99 | | | | | | 0.93 | | | 1.00 |
| 100 | | | | | | | | | 1.00 |
| 101 | | | | | | | | | 1.00 |
| 102 | | | | | | | | | 1.00 |

* It should be noted that while the first scenario is unconstrained, the second one is subject to the constraint that the harvesting tasks have to be divided in four consecutive weeks and in addition the third one has been forced to sell in four mandatory points, which have been highlighted.

In all the three scenarios both positive profits and better-than-expected environmental and quality results were obtained. As expected, taking the initial alternatives as a benchmark of the improvements achieved, it is possible to conclude that the strategy found in the three cases have improved the results of the initial alternatives. Specifically, the first scenario, in which as in the initial alternatives there are no constraints, has managed to improve the best economic result initially obtained by more than 40%. This shows how defining a good strategy has a direct effect on profitability and competitiveness of a company, even in more complex scenarios.

Furthermore, when the three scenarios are compared, it should be noted that the economic profitability obtained decreases with increasing operational or commercial constraints. This is explained by the limitation in the selection of the optimal week that the system receives when looking for the best alternative.

Table 9. Comparison of economic, environmental and product quality results of the company under each scenario.

| | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| **Economic Criteria** | | | |
| Profit (USD) | 49,844 | 47,496 | 45,263 |
| **Environmental Criteria** | | | |
| Organic Feed (%) | 50 | 50 | 50 |
| Fish in-Fish out Ratio | 0.57 | 0.60 | 0.66 |
| Total N (t) | 2.71 | 2.86 | 2.74 |
| Total P (t) | 0.55 | 0.58 | 0.57 |
| Energy Use (MJ equiv.) | $1.54\ 10^8$ | $1.63\ 10^8$ | $2.10\ 10^8$ |
| Global Warming (kg $CO_2$ equiv.) | $1.30\ 10^7$ | $1.38\ 10^7$ | $1.60\ 10^7$ |
| **Product Quality Criteria** | | | |
| Fish origin feed (%) | 45 | 45 | 45 |
| Omega-3 (%) | 1.5 | 1.5 | 1.5 |

*Each scenario represents an increasingly complex situation, where the optimization process is subject to more and more operational and commercial constraints.

Regarding the effective functioning of the Particle Swarm Optimization process in this case, we have analysed the steps taken by the methodology towards the most promising regions of the search space. With this aim, figure 4 shows the evolution of the closeness to the ideal solution of the best strategy found in each scenario step by step.

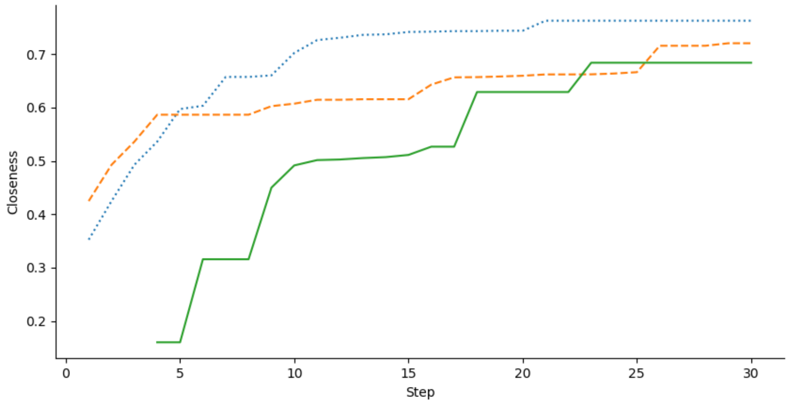

Fig. 4. Evolution of the closeness to the ideal solution step by step for the first (dotted), second (dash) and third (solid) scenario.

As can be seen, the process is working and the particles are moving in the right direction, thus improving the closeness to the ideal solution. Furthermore, figure 4 shows how in the first scenario the optimization process improves the results bit by bit, but it is slightly different when several constrains are introduced. In those cases, it is more difficult to find a feasible and good enough solution so there are only a few steps in which the closeness significantly improves.

## 4.5. Discussion and conclusions

The present study presents a methodology that integrates a multi-criteria model and a Particle Swarm Optimization (PSO) technique, thus making it possible to address the operational and strategic decision-making in aquaculture farms in a cost-effective way. This methodology has shown its great capacity not only for simulating the fattening process in aquaculture farms with multiple cages and batches, but also for finding near-optimal solutions in complex scenarios. Moreover, it responds to an actual need in aquaculture about developing methodologies that combines multi-batch culture and multiple-criteria decision-making optimization in order to be able to make better decisions (Domínguez-May, Poot-López, Hernández, Gasca-Leyva, 2020). On this basis, there are several reasons to conclude that this methodology is genuinely able to substantially improve the management capacity of fish producers by making it easier for them to carry out their role of setting long-term plans.

Firstly, the integration of a multi-criteria model has enabled us to systematically link the biologic variables of aquaculture farms management with its economic, environmental and product quality results. This opens the possibility for aquaculture producers to actively seek a strong role in the global context of changes in production and consumption patterns, considering new ways of production which are adapted to their own needs and legal requirements in terms of feed ingredients or maximum stocking density. Over the past decades, several studies have highlighted the absence of well-documented multi-criteria systems for aquaculture (Mardle & Pascoe, 1999; Mathisen et al., 2016). In this regard, some works have started to respond to this need. El-Gayar and Leung (2001) developed a model for the planning of regional aquaculture in developing countries, Martinez-Cordero and Leung (2004) analysed the use of environmentally adjusted indicators to assess the performance of aquaculture farms and, others develop modern methods applied to some specific decisions in aquaculture, such as the site selection in sea farms (Dapueto et al. 2015; Shih, 2017) or the feeding strategy (Luna et al., 2019b). However, the methodology developed in this paper represents a step forwards since it allows most operational and strategic decisions to be optimized based on multiple criteria at the same time.

Furthermore, this PSO methodology directly addresses one of the key challenges in aquaculture in recent years, the ultimate goal which is to improve efficiency in order to minimize the use of resources and maximize profits. Bjorndal Lane, and Weintraub (2004) analysed the different operations research tools applied to this end in aquaculture throughout the 20th century and stressed that the better management practices will play an increasingly vital role in this sector. In recent years, new models and Decision Support Systems have also been developed (Hargrave, 2002; Halide, Stigebrandt, Rehbein, McKinnon, 2009; Cobo et al., 2018), but they are still subject to restrictions due to the type of models applied or different aspects such as the complexity of applying them to large farms with many cages. In this respect, the optimization method developed in the present work allows farms to finally achieve the goal of overcoming central aquaculture-specific constraints and gaps in this field, such as the integration of several cages and cycles in a synchronized strategic plan. Furthermore, another important innovation made is the consideration of the operational capability and the existence of commercial agreements with large retailers that demand a continuous supply of products throughout the year.

This decision of considering operational and commercial constraints has proven to be a well-founded decision, not only because the existence of labour and market constraints is inevitable in this sector, but also because of the great impact that the commercial agreements have on the strategic planning. These agreements represent a reduction in the uncertainty surrounding company sales, which is very important in a risk sector such as aquaculture, but, at the same time, increases the management complexity due to the difficulty of complying with them on certain dates. In this way, the present study confirmed once again, the capacity of these optimization methodologies to obtain good results for the company not only in traditional multi-objective problems, but also in complex Constrained Optimization (CO) ones (Parsopoulos & Vrahatis, 2002b).

Regarding the results section, it shows how in all the three scenarios this methodology has found a feasible strategy that, moreover, presents good economic profits while also taking all the other variables into consideration. In addition, the evolution from the firsts alternatives found to the final solution achieved shows a high improvement in the company results, which proves the utility of strategic planning optimization in aquaculture. This aspect had been stated on other occasions as a way to reduce the volatility caused by operational or strategic risks (Luna, 2002), although there are still other hardly avoidable risks, such as biological or even market and price risks (Fernández-Polanco & Llorente, 2019).

Lastly, this work points out future lines of research to continue with the advance in the efficiency of the optimization process and, then, in the applicability of these methods in aquaculture farming practice. To make progress in the improvement of these optimization methods requires to balance the trade-off between exploration and exploitation when searching for new strategies. In this case, there are three components that influence the movements of particles, which could greatly improve the efficiency of the process, as shown by Shi and Eberhart (1998). After this, regarding the second line of research, new studies should seek to overcome deterministic models that do not yet completely incorporate the real uncertainty that exists in the industry. This uncertainty leads to a high volatility in the results obtained in theoretically similar situations, so any effort aimed at increasing information collection and transparency will improve these methods.

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# Capítulo 5

## *A fuzzy approach to decision making in sea-cage aquaculture production*

## A fuzzy approach to decision making in sea-cage aquaculture production.

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(forthcoming)


### Abstract

Despite the rapid growth of productivity and business production scale of aquaculture companies in the last few years, their economic results have still experienced very high volatility. This can be partly explained by the increasing complexity of management issues and the strong changes in seafood consumption patterns. But, above all else, companies' results are affected by the conditions of high uncertainty in the decision-making processes, due to the large number of biological, technical, economic and environmental influencing factors, many of them beyond the control of managers. In this context, the number of variables, scenarios and the volume of data to be considered in decision making is increasing and, therefore, technological advances are becoming much more accepted and requested. This work presents a fuzzy model that allows aquaculture producers to easily manage the uncertainty regarding climate change and market price scenarios when they are facing production decisions, such as the choice between traditional or ecological production. To that end, this novel approach uses the fuzzy pay-off method to estimate the companies' economic performance and a discrete multicriteria decision-making technique (fuzzy TOPSIS) to integrate economic, environmental and product quality criteria in the selection of the most appropriate production alternative.



### Keywords:

Aquaculture; multicriteria decision-making; fuzzy TOPSIS; fuzzy pay-off

## Resumen en español

Durante las últimas décadas, la industria acuícola ha estado expuesta a una gran volatilidad de sus resultados económicos que, a pesar del crecimiento experimentado, ha provocado diferentes crisis de rentabilidad. Hasta ahora, esto se ha intentado solucionar abordando la creciente complejidad de los problemas de gestión y los fuertes cambios en los patrones de consumo de pescado. Pero, sin embargo, las nuevas tecnologías y sistemas de gestión, mayoritariamente deterministas, han aportado pocas opciones para solucionar la influencia de la incertidumbre en torno a diferentes factores en los procesos de toma de decisiones.

Esta incertidumbre se debe principalmente a la dificultad que supone predecir la evolución de algunos factores que inciden de forma importante en los resultados de las empresas, como la temperatura del agua asociada al cambio climático o el precio de mercado de las especies ofertadas. Además, esta aumenta aún más cuando los productores se enfrentan a nuevas inversiones o nuevas formas de producción cuya evolución depende de su capacidad para responder a las demandas del mercado. Esto explica las limitaciones en el desarrollo del sector acuícola en algunos aspectos, como la transformación del producto o la oferta de productos orgánicos, a pesar de estar liderando los cambios en otros sectores.

En este contexto, el objetivo de este trabajo ha sido el desarrollo de una metodología de apoyo a la toma de decisiones en acuicultura que considere la incertidumbre en torno a los factores relacionados con el cambio climático y los escenarios de precios de mercado cuando se afrontan decisiones estratégicas, como la elección entre producción tradicional o producción ecológica.

### Metodología

Con el objetivo de dar un paso hacia la consideración de la incertidumbre en el proceso de toma de decisiones, el presente artículo introduce el uso de la teoría de conjuntos difusos y sus extensiones en los modelos desarrollados. De esta forma, se han tenido en cuenta dos fuentes de incertidumbre, la potencial variación en la evolución de algunos factores y las posibles dudas de los decisores en cuanto a sus preferencias acerca de múltiples criterios a veces opuestos y/o subjetivos.

Para ello, en primer lugar, se ha aplicado el método fuzzy pay-off para estimar el valor actual de la producción. De esta forma, es posible realizar dicha estimación en función de sus resultados en tres posibles escenarios de evolución, el más posible basado en datos históricos y dos escenarios extremos, debidos a posibles fluctuaciones de los factores clave. En segundo lugar, se ha utilizado una variación difusa de la técnica TOPSIS para integrar esa estimación con otros criterios difusos, como la sostenibilidad ambiental y la calidad del producto, respondiendo a las valoraciones cualitativas de los productores en cuanto a la importancia de cada uno d ellos.

Este modelo constituye un enfoque novedoso en acuicultura que responde a la creciente necesidad de sistemas de ayuda a la toma de decisiones que consideren el riesgo de cada alternativa.

Resultados

La aplicación de la metodología desarrollada en este estudio para abordar una decisión estratégica, como es la elección entre los métodos de producción tradicional o ecológica, ha confirmado la bondad de las metodologías difusas para apoyar el proceso de toma de decisiones en situaciones de incertidumbre.

En este sentido, esta metodología ha permitido descartar alternativas a priori más beneficiosas debido a su alta volatilidad en un sector formado por productores especialmente adversos al riesgo. Además, la metodología TOPSIS difusa ha demostrado su utilidad para facilitar la evaluación de la importancia de cada criterio por parte de los productores a través de valoraciones cualitativas.

Por todo esto, la metodología desarrollada constituye un progreso sustancial para satisfacer las necesidades específicas en el desarrollo de modelos de investigación operativa en acuicultura, que no solo facilita su aplicación práctica, sino también la consideración de nuevos criterios, como el riesgo operativo o estratégico de algunas decisiones.

## 5.1. Introduction

Aquaculture is the animal production that has grown the most in recent years due to the evolution of extensive and semi-extensive systems towards industrial scale production. At present, its production level has reached that of fisheries and it has been pointed out by FAO as the economic activity that can guarantee the sustainability of fishery resources. This process has been possible mainly thanks to the development of new production technologies. However, the rapid growth of productivity has significantly increased the complexity of aquaculture companies' management, which is affected by biological, technical, environmental, economic and market factors, many of them, beyond the control of managers. Furthermore, the greater activity has been accompanied by an increase in the volume of information that managers cannot process on their own efficiently. As a consequence, companies increasingly demand new simulation and optimization tools that help to improve the efficiency of decision making processes in aquaculture operations.

In addition to the complexity of the operations, the evolution of several uncontrollable factors for the production process is increasingly uncertain, such as water temperature or market prices. More specifically, water temperature is always highlighted as one of the key variables affecting sea cage aquaculture results both in terms of fish growth and mortality. In the case of this exogenous factor, in the short-term the company can overcome that lack of control by forecasting its value based on historical data, but it is nearly impossible to predict the exact values the will encounter in the future, mainly due to the direct effect of climate change. According to the latest IPCC report (IPCC, 2019), over the 21st century, the ocean is projected to be subject to unprecedented conditions with increased temperatures (virtually certain) and possible extreme events. Moreover, FAO have concluded in their technical report FAO (2018a) that climate change will potentially have both favourable and unfavourable impacts on aquaculture, but the available information indicates that unfavourable changes will outweigh the positives. At the same time, the strong development of the aquaculture sector has also increased market competitiveness and volatility in sale prices, facilitated by the increase in international trade (Fernández-Polanco and Llorente, 2019) and its dependence on the size of commercial fish (Janssen et al., 2017), which have important implications when planning production.

Furthermore, uncertainty increases even more when producers face new investments or new forms of production which will evolve according to how well they meet consumer demands, this makes it more difficult to predict their evolution over the next few years. This can be seen in some cases, such as organic aquaculture, which has had a high volatility of results and still has not taken off, even though organic production is leading changes in many sectors. In this regard, despite the fact there are consumers that have the capacity and willingness to pay for organic aquaculture products (Zander and Feucht, 2017), one of the main unknowns is if the plus that is produced in the final sale price would allow producers to address the increase in costs of this type of production. This situation is generated in part by a lack of tools that allow aquaculture managers to consider targets different from the economic ones, such as product quality or organic production, when making operational and strategic decisions.

Many studies worked in modelling the influence of several factors such as fish size, water temperature and feed in the fish grow (Seginer, 2016). However, these works in general present limitations in predicting the expected weight of the fish during the production process and, therefore, take some operational decisions. In recent years, researchers have developed a greater number of works that apply new bioeconomic models, and new simulation and optimization techniques to aquaculture (Granada et al., 2018; Llorente and Luna, 2015). These studies have provided new tools that improve the efficiency of decision making processes. However, these decision-making support systems usually apply deterministic models that do not take into account the real uncertainty that exists in the different biological, technical, economic and environmental factors that lead to a high variability of results obtained in theoretically similar situations. This constitutes a limitation not only when applying them in practice, but also when considering certain criteria, such as the operational risk of some decisions, in decision-making models. Regarding this uncertainty, although in the short term it is easier to estimate (with a high probability) the value of some of the factors that influence aquaculture processes and their deviations, there are situations that greatly hinder that consideration.

In this context, the aim of this work is the development of a methodology for the decision-making process in aquaculture that takes into account the uncertainty regarding climate change and market price scenarios when they are facing production decisions, such as the choice between traditional or ecological production. Pelissari et al. (2018) identify the different types of uncertainty that occur in input data of multi-criteria decision making (MCDM) problems and the most appropriate techniques to deal with each one of these uncertainties. They identify three types of uncertainties in input data: due to ambiguity, randomness and partial information, and propose a framework that indicates techniques used in different decision-making contexts for each uncertainty. Taking into account the type of uncertainty in the data, the need to deal with numerical ranges and the possibility that decision-makers express hesitancy in stating their preferences, the proposed framework recommends the use of fuzzy set theory and its extensions. For this reason, the present work uses the fuzzy pay-off method first to allow aquaculture producers to estimate the company's economic performance, then the fuzzy TOPSIS technique to integrate that estimation with other fuzzy criteria, such as the environmental sustainability and product quality (Luna et al., 2019b). This models constitutes a novel approach to fish farming in sea cages and allows producers to overcome a growing need for new decision-making methodologies and support systems.

After this introduction, the second section presents a review of the literature on applications of operational research in aquaculture. After that, section 3 explains two methodologies for decision-making under fuzzy criteria: the fuzzy pay-off method and fuzzy TOPSIS. The fourth section then describes the fuzzy model developed for aquaculture production in sea cages. Once the methodology developed has been shown, the next section presents the results of a practical example developed to test the efficiency of the model. The last section discusses the main implications of the research and present the main conclusions.

## 5.2. Operational research models in aquaculture

Fish farming began to develop industrially in the early nineties in different species such as salmon, seabream or seabass, thanks to the development of cage production technology at sea. At present, it is one of the technologies that brings greater value to aquaculture, since the production and profitability of these species grew strongly during the last 15 years. However, despite this rapid expansion of aquaculture production, there isn't much substantial literature in the field of operational research and applied economics compared to other industries (Mathisen et al., 2016). This can be partly explained by the fact that during the early stages all efforts were focused on the factors that guarantee its biological viability and allow it to develop the production on an industrial scale (Luna, 2002). However, over time, production technology became universal and prices began to decrease, so the main aquacultures industries, such as the salmon-farming industry, are entering into the maturity phase and their growth has slowed down showing an annual rate of 4% (FAO, 2018b). In this new context, the research efforts are pursuing new objectives such as the productivity and profitability improvement.

During the last decades, a large part of the increase in the expansion of the production of some species can be explained by the productivity gains, with higher survival and growth rates (Asche et al., 2003). In that context, the application of operational research models to aquaculture, integrating biological models for fish growth and economic models linking the biological production process to the market, has proven to be a success (Bjørndal et al., 2004). The first works in this area were applied to the modelling of the production of shrimp (Karp et al., 1986; Leung and Shang, 1989) and to optimize the harvesting times of salmon, under different cost scenarios (Bjørndal, 1988) or in relation with the feeding strategy (Arnason, 1992; Mistiaen and Strand, 1998).

In recent times, such methodologies were continually expanded with the main objective of determining the production plan that maximizes the value of production (Bjørndal and Asche, 2011). In addition, as Llorente and Luna (2015) highlight in their review study, some of the methodological developments included all the technical work needed to transfer the knowledge to the industry. In this way, different Decision Support Systems were developed to assist managers in their decision-making about crucial aspects, such as the seeding and harvesting schedules (Yu et al., 2007, 2010), sustainable management (Conte and Ahmadi, 2010), site selection (Halide et al., 2009) and sequencing a large number of batches in an optimal way (Cobo et al., 2019). However, no suitable solution has yet been proposed to fully fit with the realities of the huge variety of problems affecting aquaculture companies. In this regard, more attention should be paid on aspects, such as the application of multi-criteria decision making models (MCDM) and or the consideration of the uncertainty in growth and mortality, which are being increasingly studied in other industries of the primary sector (Bjørndal et al., 2012).

Regarding the MCDM techniques, several exhaustive reviews on the literature of aquaculture business management have highlighted the lack of models that allow producers to take conscious decisions based on multiple criteria (Mardle and Pascoe, 1999; Mathisen et al., 2016). Now, a few authors have integrated multi-criteria methodologies in their OR models as, for example, Dapueto et al. (2015), Shih (2017) or Luna et al. (2019a, b). But, there is a clear imbalance between economic or financial studies and those that takes into account the social and environmental criteria (Peñalosa et al., 2019).

On the other hand, the research studies and projects that address the high uncertainty in aquaculture business management made little progress. Thus, the works of Sparre (1976), using the Markov approach for optimizing the harvest, and Hatch and Atwood (1988) incorporating risk with a risk programming model into an aquaculture decision-making technique, were groundbreaking projects. The Markov approach has been repeatedly applied in several works (Leung and Shang, 1989; Leung et al., 1990; Jensson and Gunn, 2001; Bravo et al., 2013) in which future uncertain growth depends solely on the latest growth measurement. However, this is not sufficient to address all the existing sources of uncertainty, as already explained in the introduction.

## 5.3. Decision-making under fuzzy criteria

### 5.3.1. Fuzzy modelling

All the aspects already mentioned point to a gap of appropriate models in aquaculture, which the present work has the aim of closing with the utilization of fuzzy numbers and MCDM methodologies to address the uncertainty of aquaculture processes and reduce the volatility of companies' results in a novel way in this sector. To this end, the theory of fuzzy sets is used to assess the results of multiple criteria in different scenarios. In this way, the fuzzy pay-off method, a specific methodology developed by Collan et al. (2009), is applied to address the particular complexity of the profitability analysis, since it is focused on using different cash-flow scenarios as a basis for creating a possibilistic pay-off distribution for an investment. It relies on the fact that possibility theory and fuzzy numbers can be used to model imprecise investment cash-flows (Kuchta, 2000) and, in addition, is compatible with uncertainty scenarios based on expert assessments. These are important advantages over other methods in the present case since the estimation of the evolution of some crucial factors is especially complex. Furthermore, it has already been used for investment analysis and valuation in the case of patents (Collan and Heikkilä, 2011) and information systems (You et al., 2012) or R&D projects (Collan and Luukka, 2014), among others.

Zadeh (1965) introduced the theory of fuzzy sets to model the concept of vagueness, characteristic of human thought. A fuzzy set $A$ is characterized by a membership function $\mu_A(x)$ which associates a real number $\mu_A(x) \in [0,1]$ to any element $x$ in a referential set $X$. The value $\mu_A(x)$ is interpreted as the membership grade of $x$ in the set $A$. A fuzzy number is a fuzzy set with referential set $X = R$ and a membership function $\mu$ satisfying the following properties: normal ($\exists x_0 \in R$ with $\mu(x_0) = 1$), upper semi-continuous, fuzzy convex ($\mu(\lambda x + (1 - \lambda y)) \geq \min\{\mu(x), \mu(y)\}$) and compactly supported (the closure of $\{x \in R: \mu(x) > 0\}$ is compact). Fuzzy numbers allow us to face problems in which the variables or criteria are not precisely defined.

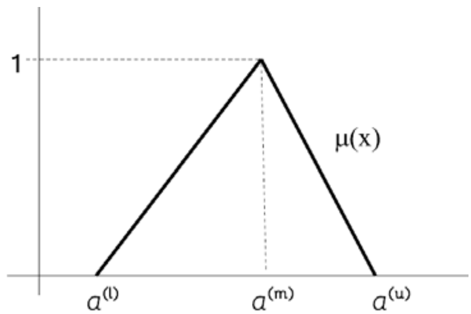


Fig. 1. Graphical representation of the fuzzy triangular number $\hat{a} = \langle a^{(l)}, a^{(m)}, a^{(u)} \rangle$.

One of the most popular types of fuzzy number is the triangular fuzzy number, that is defined by three real numbers, expressed as $\hat{a} = \langle a^{(l)}, a^{(m)}, a^{(u)} \rangle$, where $a^{(l)}$ is the lower limit, $a^{(m)}$ the most promising and $a^{(u)}$ the upper limit value. The membership function of $\hat{a}$, shown in Fig. 1, is given by:

$$\mu_{\hat{a}}(x) = \begin{cases} 0 & \text{if } x < a^{(l)} \text{ or } x > a^{(u)} \\ \frac{x - a^{(l)}}{a^{(m)} - a^{(l)}} & \text{if } x \in [a^{(l)}, a^{(m)}] \\ \frac{a^{(u)} - x}{a^{(u)} - a^{(m)}} & \text{if } x \in [a^{(m)}, a^{(u)}] \end{cases} \quad (1)$$

The assumption of triangular fuzzy numbers is a simplification, which can be frequently found in the literature and which facilitates fuzzy arithmetic calculations (Meixner, 2009). It is possible to use the operation laws following Zadeh's extension principle via this simplification which makes calculations much easier. Given the triangular fuzzy numbers $\hat{a} = \langle a^{(l)}, a^{(m)}, a^{(u)} \rangle$ and $\hat{b} = \langle b^{(l)}, b^{(m)}, b^{(u)} \rangle$, the basic addition and non-negative scalar multiplication operations are also triangular fuzzy numbers:

$$\hat{a} + \hat{b} = \langle a^{(l)} + b^{(l)}, a^{(m)} + b^{(m)}, a^{(u)} + b^{(u)} \rangle$$

$$\lambda\hat{a} = \langle \lambda a^{(l)}, \lambda a^{(m)}, \lambda a^{(u)} \rangle \text{ with } \lambda \geq 0$$

The result of the multiplication $\hat{a} * \hat{b} = \langle a^{(l)} b^{(l)}, a^{(m)} b^{(m)}, a^{(u)} b^{(u)} \rangle$ is not necessarily a fuzzy number, however we can accept this operation as an approximate value. The calculation of the distance between two fuzzy numbers can be performed in different ways. In this work we will use the vertex method used by Chen (2000):

$$d(\hat{a}, \hat{b}) = \sqrt{\frac{1}{3}\left[(a^{(l)} - b^{(l)})^2 + (a^{(m)} - b^{(m)})^2 + (a^{(u)} - b^{(u)})^2\right]} \quad (2)$$

On certain occasions, it may be appropriate to replace a fuzzy number with an exact number (crisp number). Defuzzification is the process of converting a fuzzy number into a single crisp value in the referential set. There are many different methods of defuzzification available, we will use the centroid of area (COA) method that provides a crisp value based on the center of gravity of the fuzzy set. For continuous membership function $\mu_{\hat{a}}(x)$ is defined as:

$$df(\hat{a}) = \frac{\int_{-\infty}^{\infty} x \mu_{\hat{a}}(x) dx}{\int_{-\infty}^{\infty} \mu_{\hat{a}}(x) dx} \quad (3)$$

In the case of triangular fuzzy numbers we can calculate the gravity center of the fuzzy number over any subinterval $[p,q]$ in the following manner:

$$df_{[p,q]}(\hat{a}) = \frac{2}{a^{(u)}-a^{(l)}} \int_p^q x\, \mu_{\hat{a}}(x)dx \quad (4)$$

Another crisp measure associated with fuzzy numbers is the possibilistic or fuzzy mean of a fuzzy number $\hat{a}$, that is computed using the concept of $\alpha$-cuts. Given a fuzzy number and a value $\alpha \in [0,1]$, the $\alpha$ −cut is defined as $[\hat{a}]^{\alpha} = \{x \in R: \mu_{\hat{a}}(x) \leq \alpha\}$ and is a closed interval $[a_1(\alpha), a_2(\alpha)]$. According to Carlsson and Fullér (2001) the possibilistic (or fuzzy) mean value of fuzzy number $\hat{a}$ with $\alpha$-cuts $[\hat{a}]^{\alpha} = [a_1(\alpha), a_2(\alpha)]$ is defined as

$$E(\hat{a}) = \int_0^1 (\, a_1(\alpha) + a_2(\alpha))\alpha d\alpha \quad (5)$$

In the particular case of a fuzzy triangular number $\hat{a} = \langle a^{(l)}, a^{(m)}, a^{(u)} \rangle$, the $\alpha$-cuts are

$$[\hat{a}]^{\alpha} = [a^{(l)} + \alpha(a^{(m)} - a^{(l)}), a^{(u)} - \alpha(a^{(u)} - a^{(m)})]$$

and the fuzzy mean is

$$E(\hat{a}) = \frac{1}{6}(a^{(l)} + a^{(u)} + 4a^{(m)}) \quad (6)$$

### 5.3.2. Fuzzy pay-off method

The fuzzy pay-off method was introduced by Collan et al. (2009) as a method for the valuation of projects and assets. They define the real option value (ROV) from a fuzzy net present value (NPV) as

$$ROV = \frac{\int_0^{\infty} \mu_{\hat{A}}(t)dt}{\int_{-\infty}^{\infty} \mu_{\hat{A}}(t)dt} \times E(\hat{A}_+) \quad (7)$$

where $\hat{A}$ represents the fuzzy NPV, with membership $\mu_{\hat{A}}(x)$ and $E(\hat{A}_+)$ representing fuzzy mean value of the positive side of $\hat{A}$. When the whole fuzzy number is above zero, then ROV is the fuzzy mean of the fuzzy number calculated by expression (5), and when the whole fuzzy number is below zero, the ROV is zero.

Hassanzadeh et al. (2012) use the fuzzy pay-off method to effectively value R&D projects and include expressions to compute $E(\hat{x}_+)$ with trapezoidal fuzzy numbers. These expressions can easily be adapted to the case of triangular numbers $\hat{x}$:

$$E(\hat{x}_+) = \begin{cases} E(\hat{x}) = \frac{1}{6}\left(x^{(l)} + x^{(u)} + 4x^{(m)}\right) & \text{if } x^{(l)} \geq 0 \\ \frac{1}{6}\left(x^{(l)} + x^{(u)} + 4x^{(m)} + \left(x^{(m)} - x^{(l)}\right)\left(1 - \frac{x^{(m)}}{x^{(m)} - x^{(l)}}\right)^3\right) & \text{if } x^{(l)} < 0 \leq x^{(m)} \\ \frac{1}{6}\left(x^{(u)} - x^{(m)}\right)\left(1 + \frac{x^{(m)}}{x^{(u)} - x^{(m)}}\right)^3 & \text{if } x^{(m)} < 0 \leq x^{(u)} \\ 0 & \text{if } x^{(u)} < 0 \end{cases} \quad (8)$$

The calculation of ROV using (7) implies the multiplication of the possibilistic mean of the positive outcome $E(\hat{x}_+)$ by the fraction of positive area of the distribution of the NPV. In the case of a fuzzy triangular number $\hat{x}$ this fraction is

$$\frac{\int_0^\infty \mu_{\hat{x}}(t)dt}{\int_{-\infty}^\infty \mu_{\hat{x}}(t)dt} = \frac{2}{x^{(u)} - x^{(l)}} \int_0^\infty \mu_{\hat{x}}(t)dt \quad (9)$$

where

$$\int_0^\infty \mu_{\hat{x}}(t)dt = \begin{cases} \frac{1}{2}\left(x^{(u)} - x^{(l)}\right) & \text{if } x^{(l)} \geq 0 \\ \frac{1}{2}\left(x^{(u)} - x^{(l)} - \left(x^{(m)} - x^{(l)}\right)\left(1 - \frac{x^{(m)}}{x^{(m)} - x^{(l)}}\right)^2\right) & \text{if } x^{(l)} < 0 \leq x^{(m)} \\ \frac{1}{2}\left(x^{(u)} - x^{(m)}\right)\left(1 + \frac{x^{(m)}}{x^{(u)} - x^{(m)}}\right)^2 & \text{if } x^{(m)} < 0 \leq x^{(u)} \\ 0 & \text{if } x^{(u)} < 0 \end{cases} \quad (10)$$

### 5.3.3. Fuzzy discrete multicriteria decisión-making: fuzzy TOPSIS

Discrete MCDM are used to assess a finite set of alternatives in order to select a suitable alternative to fulfil a desired goal with regard to multiple (and often conflicting) criteria. MCDM is recognized as a significant and active area of operational research and management science. Different decision-making methods have been developed and used for different real-life problems and there are no superior methods (Ishizaka and Siraj, 2018). The choice of a specific method depends on different factors concerning the problem and the method's characteristics.

Given the great diversity of MCDM methods, the first question is related to choosing the most appropriate method based on the characteristics of the problem. Although Haddad and Sanders (2018) propose a methodology to recommend the most suitable MCDM when risk and uncertainty are anticipated, Ceballos et al. (2018) argue that the question remains open. In their paper, they compare a set of MCDM methods sharing three features: same fuzzy information as input data, the need of a data normalization procedure, and quite similar information processing. Specifically, they compare different fuzzy versions of MULTIMOORA, VIKOR, WASPAS and TOPSIS methods and conclude that given a new decision problem, a good strategy would be to solve it with as many methods as possible. Other comparative studies can be taken as a reference. Rodrigues-Lima et al. (2014) present a comparative analysis of two widely applied methods for supplier selection: fuzzy TOPSIS and fuzzy AHP. Their analysis is based on seven factors: adequacy to changes of alternatives or criteria, agility in the decision making problem, time complexity, support to group decision-making, limitation in the number of criteria and alternatives, and modeling uncertainty. According to their conclusions, although both methods are adequate to deal with imprecision, subjectivity and group decision, fuzzy TOPSIS performs better than fuzzy AHP in most cases except when there are few criteria and suppliers. Fuzzy AHP is prone to ranking reversal when a new alternative is included, while fuzzy TOPSIS produces consistent preference order.

Another advantage of fuzzy TOPSIS is that there is no limitation in the number of criteria and alternative suppliers without a change in the decision problem hierarchy structure. A similar comparative study between fuzzy TOPSIS and data envelopment analysis (DEA) reveals that TOPSIS outperforms DEA in terms of both calculation complexity and sensitivity to changes in the number of suppliers (Rashidi and Cullinane, 2019). Finally, Pätäri et al. (2018) perform a comparison of median-scaling (MS), TOPSIS, AHP, and add.DEA in the context of portfolio selection and, at least for their particular sample data, AHP and TOPSIS outperform MS and add.DEA. Another advantage of the TOPSIS method is its possibility of offering a graphical display that is very appealing to decision makers (Eiselt and Marianov, 2014).

For the reasons outlined above, in this work we decided to use a fuzzy extension of TOPSIS. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multicriteria decision making method originally developed by Hwang and Yoon (1981) that considers two hypothetical alternatives: the positive-ideal (with the best values for all the attributes) and the negative-ideal (with the worst values for all the attributes), to later measure a closeness ratio in order to choose the alternative with the shortest distance from the positive ideal solution and longest distance from the negative ideal solution.

Different fuzzy extensions of TOPSIS can be found in the scientific literature; variations of fuzzy TOPSIS focus on the determination of ideal solutions, distance measurement or the use of different type of fuzzy numbers. We have chosen to use the methodology proposed by Chen (2000) due to its simplicity and applicability. The methodology is briefly described below.

*Input.* A fuzzy decision matrix and weight vector:

$$\hat{\mathbf{X}} = \begin{pmatrix} \hat{x}_{11} & \hat{x}_{12} & \cdots & \hat{x}_{1m} \\ \hat{x}_{21} & \hat{x}_{22} & \cdots & \hat{x}_{2m} \\ \cdots & \cdots & \ddots & \cdots \\ \hat{x}_{n1} & \hat{x}_{n2} & \cdots & \hat{x}_{nm} \end{pmatrix}; \quad \hat{\mathbf{w}} = \begin{pmatrix} \hat{w}_1 \\ \hat{w}_1 \\ \vdots \\ \hat{w}_m \end{pmatrix}$$

where $\hat{x}_{ij}$ represents the fuzzy rating of alternative $i$ under criterion $j$, and $\hat{w}_j$ the importance fuzzy weight of criterion $j$.

*Step 1.* Construct the normalized fuzzy decision matrix $\hat{\mathbf{R}} = (\hat{r}_{ij})_{n\times m}$, where

$$\hat{r}_{ij} = \begin{cases} \langle \frac{x_{ij}{}^{(l)}}{u_j^+}, \frac{x_{ij}{}^{(m)}}{u_j^+}, \frac{x_{ij}{}^{(u)}}{u_j^+} \rangle & if\ j\ is\ a\ benefit\ (\max)\ criterion \\ \langle \frac{l_j^-}{x_{ij}{}^{(u)}}, \frac{l_j^-}{x_{ij}{}^{(m)}}, \frac{l_j^-}{x_{ij}{}^{(l)}} \rangle & if\ j\ is\ a\ cost\ (\min)\ criterion \end{cases}$$

with $u_j^+ = \max_i x_{ij}^{(u)}$ and $l_j^- = \min_i x_{ij}^{(l)}$

*Step 2.* Construct the fuzzy weighted normalized decision matrix $\hat{\mathbf{V}} = (\hat{v}_{ij})_{n\times m}$, where $\hat{v}_{ij} = \hat{r}_{ij} * \hat{w}_j$ are normalized positive triangular fuzzy numbers in $[0,1]$.

*Step 3.* Identification of fuzzy ideal ($\hat{v}_j^+$) and anti-ideal ($\hat{v}_j^-$) values for each criterion. In the case of benefit criterion $\hat{v}_j^+ = \hat{1} = \langle 1,1,1 \rangle$ and $\hat{v}_j^- = \hat{0} = \langle 0,0,0 \rangle$, and in the case of cost criterion $\hat{v}_j^+ = \hat{0}$ and $\hat{v}_j^- = \hat{1}$.

*Step 4.* Calculate the closeness coefficient of each alternative:

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

where $D_i^+ = \sum_j d\,(\hat{v}_{ij}, \hat{v}_j^+)$ and $D_i^- = \sum_j d\,(\hat{v}_{ij}, \hat{v}_j^-)$ using the distance measure (2).

*Step 5.* Rank the alternatives according to the closeness coefficient (the alternative with the higher value is preferred).

TOPSIS and fuzzy TOPSIS are based on synthesizing criteria; the ratings for all the criteria are aggregated into a single overall grade (closeness coefficient) allowing a bad rating for one criterion to be compensated for a good rating in another.

## 5.4. Product decisions in a fuzzy context

When addressing product decisions, it is necessary to take into account the physical, service and subjective attributes of each product. In the case at hand, these aspects depend on decisions such as the species of fish we are going to produce or the size category that we have as a production objective. However, recently, the decision between traditional and organic products has gained special importance for producers. This decision is mainly marked by only two decisions, the fry that will be introduced into the cage and the feeding strategy that will be carried out. However, this has great importance due to several factors:

- The decision has to be taken at first, since it affects the initial costs of buying fingerlings, and is hardly reversible without assuming the loss of part of those costs.
- Most of the company's costs will be determined by the feeding strategy, which represents between 30%–60% of total production costs (Goddard, 1996).
- Uncertainty is multiplied when the producer faces new forms of production that depend on a new factor: the valuation of customers about the plus price that these products deserve.

For these reasons the choice of the most appropriate feed has important implications for business results. In this section we propose two fuzzy approaches to select one of the available feeds already formulated by the industry.

### 5.4.1. Fuzzy farming model

In order to simulate the results obtained with the different farming alternatives in aquaculture it is necessary to apply a biological model and three different submodels that simulate the economic, environmental and quality behaviour of the fattening process in the cages. This model is based on the bioeconomic model described in previous studies developed by Luna et al. (2019b) but fuzzy elements are now introduced.

The model takes the assumption that there are a range of abiotic factors (temperature, light, salinity, and oxygen) in which, as the process is done in sea cages, the producer cannot influence in an economically efficient way (Brett, 1979). Neither is it possible to choose the maximum biomass density, which is equal to the maximum insurable biomass density (Luna, 2002) or to the maximum allowed density in the case of ecologic labelled production. Of these external factors, the one with the greatest influence on the growth of the fish is the seawater temperature since the producer must plan the juvenile seeding and fattening processes based on an fuzzy estimate of these temperatures at the location of the farm. In addition, now it is assumed that the value for growth and mortality rates depending on fish weight and temperature provided by feed suppliers are not an exact number. These rates depend on many factors that are hardly predictable with accuracy. In order to overcome this problem, a fuzzy extension of the previous model has been developed using triangular fuzzy numbers. This allows the model to consider the variation on the growth rates depending on the variation of the water temperature.

On the other hand, the market price is the other main external factor that plays a key role and cannot be accurately predicted. This factor is crucial for determining the optimal input mix for maximizing the value of the stock and the price uncertainty may induce further changes in optimal harvesting patterns (Bjørndal et al., 2004). In this regard, it is possible to estimate the expected price taking as reference past prices, but always considering those prices as fuzzy numbers. In addition, prices tend to be different depending on the type of production (ecologic/non-ecologic) and the range of fish weights. For example, in the case of gilthead seabream weights below 300g cannot be traded, and prices of gilthead seabream with more than 400g are higher than serving size (between 300 and 400).

In complex decision-making contexts decisions must be data-driven. The use of an appropriate database is crucial to allow the model to easily use specific information but also assists in the clarification of the problem. In the present case, as can be seen in Luna et al. (2019b), we use a database with a structure consisting of four groups of tables: First, a central axis to identify the aquaculture farm and its main characteristics. Then, two groups representing the uncontrollable variables that affect the system performance and therefore are required for forming a reliable decision (Casini et al., 2015). Lastly, the group of tables containing information about the status of each cage and the specific feeding, growth and loss rates according to the available feeds. Information used in this work has been collected from primary sources, such as oceanographic buoys or feed manufacturers, or secondary sources of information, i.e., other research studies.

Taking all these into account, the fuzzy model uses the following notations:

Model notation

| | |
|---|---|
| $\widehat{T}_t$ | fuzzy seawater temperature in period $t$ = 1,2,… |
| $\widehat{N}_t$ | fuzzy number of fish in the cage at time period $t$. |
| $\widehat{w}_t$ | fuzzy fish weight at time period $t$. |
| $M(x,T)$ | mortality rate as function of fish weight and temperature. |
| $pf(w_0, eco)$ | fingerling price depending on the weight and the type of production. |
| $n$ | number of available feeds (alternatives). |
| $eco_f$ | binary variable indicating whether the feed is suitable for ecologic production or not, $f$ = 1,2,…,$n$. |

| | |
|---|---|
| *price*$_f$ | price of feed *f*. |
| $R_f(w, T)$ | feed ration recommended by the feed producer based on fish weight and temperature, *f* = 1,2,…,*n*. |
| $GR_f(w, T)$ | estimated growth rate as function of fish weight and temperature, *f* = 1,2,…,*n*. |
| $W_{min}$ | minimum commercial weight. |
| $\hat{p}(w)$ | fuzzy estimated selling price depending on fish weight. |
| $\widehat{eplus}$ | fuzzy "plus" (%) that consumers would be willing to pay for an eco-labeled product. |

This way, assuming that we know the initial state of the cage (initial number of fish $\widehat{N}_0$ and estimated weight $\widehat{w}_0$), the evolution of the state of the cage during the fattening process using feed $f$ is modeled by equations

$$\widehat{N}_t = \widehat{N}_0 \prod_{k=0}^{t-1} \left( \hat{1} - \langle M\left(w_k^{(l)}, T_k^{(l)}\right), M\left(w_k^{(m)}, T_k^{(m)}\right), M(w_k^{(u)}, T_k^{(u)}) \rangle \right) \quad (11)$$

$$\widehat{w}_t = \widehat{w}_0 \prod_{k=0}^{t-1} \left( \hat{1} + \langle GR_f\left(w_k^{(l)}, T_k^{(l)}\right), GR_f\left(w_k^{(m)}, T_k^{(m)}\right), GR_f(w_k^{(u)}, T_k^{(u)}) \rangle \right) \quad (12)$$

Lastly, the mortality rate $M(w, T)$ also depends on the size of the fish and the seawater temperature and is estimated using biological studies and practical farming experiences.

### 5.4.2. Economic performance measurement using fuzzy pay-off method

From a conventional economic point of view, the main objective of aquaculture enterprises is profit maximization. In order to estimate operational profit, we have to consider the costs incurred in the feeding process and the revenue obtained from the sales. This study considers only the costs directly related to this decision, such as the purchase of fingerlings and feed, making the assumption that others are not influenced.

Regarding the decision-making process in aquaculture in contexts of uncertainty, it would be possible to apply the fuzzy pay-off method to choose the feed with the highest ROV calculated according to (7).

Assuming that $fp$ represents the fattening duration, the total amount of food using feed $f$ is a fuzzy number calculated as

$$\widehat{F}_f = \sum_{k=0}^{fp-1} \left( \widehat{N}_k * \langle R_f\left(w_k^{(l)}, T_k^{(l)}\right), R_f\left(w_k^{(m)}, T_k^{(m)}\right), R_f\left(w_k^{(u)}, T_k^{(u)}\right) \rangle \right) \quad (13)$$

and the feeding cost is $\hat{C}_f = price_f \hat{F}_f$. The total amount of food depends on the number of fish estimated at each moment, modeled by the fuzzy number $\widehat{N}_k$, and on the amount of feed to be supplied following the feed manufacturer's prescriptions. These prescriptions are defined by non-fuzzy functions $R_f$, so the different scenarios (lower, upper and most promising values of fish weight and temperature) must be considered in their application.

We can consider that the feeding costs are distributed throughout the different quarters of the fattening period. We will denote the total feeding cost of the quarter q as $\hat{C}_{f,q}$. Another associated production cost is the cost of fingerlings. It should also be considered that the cost depends on the fingerlings' weight and their compliance with restrictions for organic production. Assuming that $pf(w_0, eco)$ represents the unit fingerling price, the production costs are

$$\widehat{PC}_f = pf(w_0, eco)\widehat{N}_0 + \sum_{k=0}^{nq} \hat{C}_{f,q} \tag{14}$$

where $nq$ is the number of quarters of the feeding period.

The calculation of the operating income is affected by the uncertainty not only in the growth of fish, but also in market prices at the time of commercialization. The proposed model assumes that the price is different depending on the weight segment of the fish.

The income obtained from the sales is computed as:

$$\hat{I}_f = \langle \hat{p}(w_{fp}^{(l)})^{(l)}, \hat{p}(w_{fp}^{(m)})^{(m)}, \hat{p}(w_{fp}^{(u)})^{(u)} \rangle * \widehat{N}_{fp} * \widehat{w}_{fp} * (\hat{1} + eco_f \widehat{eplus}) \tag{15}$$

In order to compute this income, the sale price of the final product is considered a fuzzy number that depends not only on the uncertainty in the price itself, but also on the final weight that the fish will reach. The lower (upper) limit of the sale price is taken as the result of assuming the lower (upper) limit of the estimated price and the lower (upper) limit of the estimated fish weight. The last factor of the expression (15) allows us to consider the possibility of obtaining a fuzzy extra plus in income by opting for organic production (when $eco_f = 1$).

Cash flows allow us to calculate the fuzzy net present value (NPV) of each feeding option:

$$\widehat{NPV}_f = \frac{\hat{I}_f}{(1+r/4)^{nq}} - pf(w_0, eco)\widehat{N}_0 - \sum_{q=1}^{nq} \frac{\hat{C}_{f,q}}{(1+r/4)^q} \tag{16}$$

where $nq$ is the number of quarters of the feeding period and $r$ is the annual discount rate.

Finally, using (7) the real option value associated to each alternative can be computed and the one with highest value would be selected.

### 5.4.3. Integration of multiple criteria with Fuzzy TOPSIS

Although the economic performance of a company is usually the decision criterion in aquaculture studies, several authors have highlighted the need for a higher effort to include all aspects of sustainability in future research to help bring the industry closer to sustainable development (Peñalosa et al., 2019). In this regard, the choice between traditional and ecological production can be based on a wide range of different criteria.

Following on from previous work, such as the study developed by Luna et al. (2019b) to determine the decision criteria that play an important role in aquaculture processes, the present study considers six economic, environmental and product quality criteria.

$C_1$ Real option value (ROV): crisp number calculated using (7) and taking into account the cash-flows in the feeding process.

$C_2$ Feed conversion ratio (FCR): is a rate measuring the feed efficiency, in terms of the amount of fish based feed needed to produce a unit weight of the cultured species (Fish-in Fish-out ratio). This criterion responds to the idea that the most efficient use of resources, especially fishmeal and fish oil, is a decisive factor for sustainable aquaculture (FAO, 2018b).

$C_3$ Chemical waste (nitrogen and phosphorus): In line with the previous criterion, stakeholders placed the highest value on the prevention of chemical contamination, namely nitrogen and phosphorus, in order to minimize the environmental impact of aquaculture (Lembo et al., 2018).

$C_4$ Potential warming: prior to arriving on the farm, feed production has also an environmental impact that is commonly measured by the energy use (MJ equiv.), and the global warming potential impact (CO2 equiv.) of the greenhouse gas emissions, among others (Abdou et al., 2017). The inclusion of specific criteria, such as a carbon footprints indicator, have proven to have benefits for both the consumer and producer (Madin and Macreadie, 2015).

$C_5$ Omega-3: as Shahidi and Alasalvar (2010) explained, fatty acids, particularly omega-3, are considered as health-promoting dietary components so some feed producers present an approximate amount of omega-3 transmitted with the use of their feed during the whole fattening process based on their own empirical studies. We consider the amount of omega-3 in the feed as selection criterion.

$C_6$ Proportion of fish origin: as fatty acids are one of the main pre-harvest factors affecting quality, the amount of fishbased feed that is used in the last months of production has been included as a quality criterion. Grigorakis (2010) has shown that 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. We consider the proportion of fish origin ingredients in the feed as selection criterion.

These criteria can be divided into two categories: benefit criteria (more is better) $\{C_1, C_5, C_6\}$ and cost criteria (less is better) $\{C_2, C_3, C_4\}$.

The values of the criteria in each alternative can be calculated taking as reference the total amount of feed $\hat{F}_f$ that should be used during the fattening period calculated as (13) and the deterministic information provided by the feed producer. As these quantities depend on the environmental conditions and the size of the fish, they are also considered fuzzy numbers.

Another important aspect to consider is the fact that, if you want to offer an eco-labeled product, the Commission Regulation (EC) No 889/2008 of 5 September 2008 have set specific rules on feeds for carnivorous aquaculture animals. The most important one is that they shall be sourced by-products from organic aquaculture, fisheries certified as sustainable or organic feed materials of plant origin.

Therefore, in addition to the values of the 6 criteria, each feeding alternative must include a value of the binary variable $eco_f$, indicating whether the feed is suitable or not for obtaining the ecological label.

The values calculated for the criteria allow the construction of the fuzzy ratings matrix $\hat{\mathbf{X}}$ to later apply the TOPSIS methodology as shown in the following section.

## 5.5. Practical example

Once the model has been developed, we tested its efficiency under real operating conditions when an election between 3 production alternatives was taken: two of them would lead the decisor to produce a traditional product of greater or lesser quality, and the third one allowed him to obtain an eco-label for the product, thus obtaining a possible increase in the sale price.

With this aim, the conditions of a sea cage of gilthead seabream during a year was simulated based on historical data and possible scenarios on the evolution of key uncertain parameters. Finally, the optimal alternative was chosen for two theoretical producers.

### 5.5.1. Farm conditions

Gilthead seabream farming is commonly developed in the Mediterranean Sea, due to its favourable natural conditions. Accordingly, the specific characteristics of the cage are based on common characteristics of Mediterranean farms in Spain as shown in Table 1.

*Table 1. Farm characteristics,*

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Location | Tarragona - Spain (2720) | Cages | 1 |
| Species | Gilthead sea bream | Cage capacity | 200 $m^3$ |
| Seeding Date | 01/07/2019 (week 0) | Batches | 1 |
| Harvesting Date | 01/07/2020 (week 52) | Fingerling weight ($w_0$) | 30 g |
| Time horizon | 52 weeks | Feasible harvest sizes | 300-1000 g |

Information on sea temperature has been collected from the oceanographic buoys network of the Spanish Port Authority, that covers the principal locations of marine aquaculture in Spain. In the present study, the data registered during 2018 by the buoy placed at the simulated location, in the Mediterranean Sea near Tarragona, have been used to deduce triangular fuzzy numbers $\hat{T}_t$ for weeks $t = 1,2,\ldots,52$. The mean values $T_t^{(m)}$ of water temperature in each week of the farming period are shown in Fig. 2 and we consider the following fuzzy values to use in the fuzzy growth model:

$$\hat{T}_t = \langle T_t^{(m)} - 0.50, T_t^{(m)}, T_t^{(m)} + 1.00 \rangle$$

In relation to the sales prices of seabream, the minimum commercial size is 300g and three price segments are considered based on those from the Spanish wholesale market.

- Segment 1 (non-commercial size, less than 300g): although the income from the sale would be 0, the fish would have an accounting value and it will be assumed that this value is equal to the sale price of the first commercial segment (segment 2) with a penalty of 25%.
- Segment 2 (serving size, between 300 and 400g): price $\hat{p}(I_1) = \langle 3.57, 4.00, 4.24 \rangle$ euro/kg.
- Segment 3 (more than 400g): price $\hat{p}(I_1) = \langle 4.05, 4.60, 5.05 \rangle$ euro/kg.

In addition, the ecologic/organic plus price that consumers might be willing to pay is assumed equal to $\widehat{eplus} = \langle 0.07, 0.15, 0.20 \rangle$. This assumption is based on market studies conducted by different researchers (Zander and Feucht, 2017).

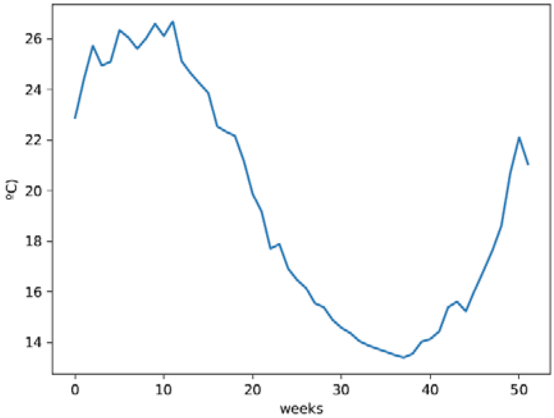

Fig 2. Evolution of water temperature during the farming period in the location.

The proposed model has been tested for three different alternatives. The main difference between them concerns the selected feed stuff, assuming that there are only three feed stuffs available in the market. The first traditional feed stuff ($F_1$) represents the more commonly used, with the best quality-price ratio; the second one ($F_2$) has an increased percentage of fish protein so, although it has a higher price, growth rates are good even under unfavorable weather conditions and the final product quality is better. On the other hand, the last feed stuff ($F_3$) is a high quality and price feed, entirely made with products from organic fisheries/production, which is used for eco-labeled production.

However, the decision has implications beyond just selecting the right feed. The maximum numbers of fingerlings have been calculated by estimating the weight they can reach depending on the type of feeding and with the restriction of not exceeding the maximum established densities at the end of the fattening period. If organic production is chosen, EU standards reduce the maximum amount of biomass that is admissible and that, in turn, has effects on the maximum number of fingerlings that can be seeded in the cage. Furthermore, organic production also requires the use of a specific type of fingerling that is usually more expensive. In this case it is assumed that the ecological fingerling is priced 50% higher than a standard one of the same weight, whose price is around 0.20 euros/unit (Janssen et al., 2017). Table 2 shows information about the implications of opting for different types of feed.

*Table 2. Available feeds.*

| Feed | Type of production | $eco_f$ | Max biomass density | Initial number of fingerlings | Unit cost of fingerlings |
|---|---|---|---|---|---|
| $F_1$ | Standard | 0 | 20 $kg/m^3$ | 12964 | 0.20 euros |
| $F_2$ | Standard | 0 | 20 $kg/m^3$ | 12400 | 0.20 euros |
| $F_3$ | Organic/Eco | 1 | 15 $kg/m^3$ | 8123 | 0.30 euros |

*Table 3. Production simulation depending on used feed.*

| Feed | $\widehat{N}_{fp}$ | $\widehat{w}_{fp}$ | centroid | $\alpha - cut$: $[\widehat{w}_{fp}]^{\alpha}$ |
|---|---|---|---|---|
| $F_1$ | <12130,12139, 12166> | <298.11,328.02, 361.25> | 329.13 | $[298.11 + 29.91\alpha, 361.25 - 33.23\alpha]$ |
| $F_2$ | <11606,11615, 11638> | <317.60,344.14,3 78.99> | 346.91 | $[317.60 + 26.54\alpha, 378.99 - 34.85\alpha]$ |
| $F_3$ | <7597,7603,76 22> | <363.86,389.22,4 30.96> | 394.68 | $[363.86 + 25.36\alpha, 430.96 - 41.74\alpha]$ |

Fig. 3 shows the evolution of the estimated weight of the fish for each alternative, representing in each case the most promising value $w_t^{(m)}$ of the fuzzy weight. As explained above, organic production implies the use of feed 3, less biomass density and, therefore, lower number of final fish (see Table 2). Nevertheless, feed 3 achieves the highest growth rates, it also has the highest quality and fish could be sold with a plus in the price, which should compensate for the increase in costs. In short, the choice of feed is not trivial, so the use of fuzzy decision-making methodologies is proposed.

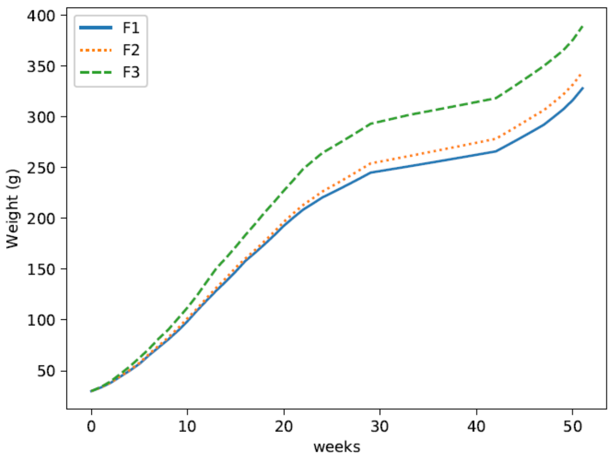


Fig 3. Evolution of fish weight.

### 5.5.2. Application of fuzzy pay-off method

Firstly, the great uncertainty that affects the aquaculture sector due to the aforementioned factors, has its greatest impact when estimating the economic performance of the production. On the one hand, if this uncertainty is not considered, an economic aspect as important as risk would be left out. On the other hand, the consideration of all possible scenarios, many of them unknown, becomes almost impossible. In order to address this problem, the fuzzy pay-off method has been applied to estimate the present value of each alternative.

With this aim, Table 4 shows the projected cash-flows for each alternative over a period of 4 quarters under conditions defined in the previous section. The table shows fingerling cost, feeding costs in each quarter and the estimated income at the end of the fattening period.

*Table 4. Cash-flow projection with the different alternatives.*

| Feed | Fingerlings cost | Feeding cost Q1 | Feeding cost Q2 |
|---|---|---|---|
| $F_1$ | <2592.80,2592.80, 2592.80> | <1690.91,1881.36, 1762.48> | <2309.29,2451.68, 2495.50> |
| $F_2$ | <2480.00,2480.00, 2480.00> | <1771.80,1956.20, 1846.45> | <2424.34,2555.10, 2633.41> |
| $F_3$ | <2436.90,2436.90, 2436.90> | <1551.66,1720.69, 1621.05> | <2205.53,2329.84, 2477.17> |

| Feed | Feeding cost Q3 | Feeding cost Q4 | Income |
|---|---|---|---|
| $F_1$ | <1323.80,1554.09, 1957.07> | <1929.73,2193.48, 2608.63> | <9689.90,15927.55, 18634.54> |
| $F_2$ | <1429.14,1655.37, 2053.35> | <2054.66,2303.25, 2725.17> | <13170.07,15988.63, 18701.25> |
| $F_3$ | <1330.30,1375.86, 1791.31> | <1847.34,2013.70, 2360.05> | <10568.00,13612.62, 19905.72> |

Using the cash-flows of Table 4 and assuming an annual discount rate $r$ = 0.04, the fuzzy NPV are calculated using expression (16) and ROV values using (7). Both values are shown in Table 5. Based on the results of this evaluation, the recommendation is to opt for the traditional production of gilthead seabream using the feed 2.

In today's conditions, however, it takes more than just choosing the alternative with the best value for the economic criterion. More than ever, economic criteria must be considered together with environmental sustainability or product quality criteria in order to provide the necessary flexibility that these methods need to be applicable in practice.

*Table 5. Fuzzy real option value with the different alternatives.*

| Feed | NPV | $E(\widehat{NPV}_f +)$ | Factor | ROV |
|---|---|---|---|---|
| $F_1$ | <-358.25,4830.88,6716.91> | 4280.64 | 0.9965 | 4265.66 |
| $F_2$ | <2683.75,4623.11,6470.05> | 4607.71 | 1.0000 | 4607.71 |
| $F_3$ | <953.94,3386.45,8652.16 > | 3858.65 | 1.0000 | 3858.65 |

## 5.5.3. Application of Fuzzy TOPSIS

The next step to take multiple criteria and their potential complications into consideration is the application of the Fuzzy Topsis methodology. As outlined in the methodological approach to this research, this method deals with each new criterion as a triangular fuzzy number to synthesize and aggregate them into a single overall grade for each decision-maker, thus allowing for a better assessment of each alternative with the aim of selecting the most suitable one.

First, the fuzzy decision matrix $\widehat{\mathbf{X}}$ with the fuzzy evaluations of each alternative (feed) with respect to each of the criteria $\{C_1, C_2, C_3, C_4, C_5, C_6\}$ is defined with the information shown in Table 6.

*Table 6. Fuzzy ratings matrix.*

| Feed | ROV ($C_1$) | FCR ($C_2$) | Chemical waste ($C_3$) |
|---|---|---|---|
| $F_1$ | 4265.66 | <0.51,0.51,0.52> | <694285.16,773428.66,844551.89> |
| $F_2$ | 4607.71 | <0.75,0.76,0.77> | <661206.99,729219.54,797102.21> |
| $F_3$ | 3858.65 | <1.04,1.05,1.05> | <612052.39,656643.93,728088.30> |

| Feed | Omega-3 ($C_5$) | Proportion of fish origin ($C_6$) | Potential warning ($C_4$) |
|---|---|---|---|
| $F_1$ | 0.01 | 0.25 | <12323931.64,13728770.96,14991246.17> |
| $F_2$ | 0.01 | 0.38 | <5851389.29,6453270.28,7054001.85> |
| $F_3$ | 0.02 | 0.55 | <8957504.98,9610110.70,10655712.86> |

Then, in order to apply the fuzzy TOPSIS methodology and construct the fuzzy weighted normalized decision matrix, the decision maker must assess the importance of each criterion using weights. These weights are the only subjective parameters taken into account in the methodology. To facilitate the decision maker's task, linguistic variables can be used. Table 7 shows the linguistic variables for the importance weight of the criteria and the equivalent fuzzy triangular numbers together with the opinions of two decision makers.

*Table 7. Fuzzy weights of each criterion.*

| | | $C_1$ (MAX) | $C_2$ (MIN) | $C_3$ (MIN) | $C_4$ (MIN) | $C_5$ (MAX) | $C_6$ (MAX) |
|---|---|---|---|---|---|---|---|
| Linguistic variable | Fuzzy weight | Importance | | | | | |
| Very low | <0.0,0.0,0.1> | | ⊗ | ⊗ | ⊗ | ⊗ | ⊗ |
| Low | <0.0,0.1,0.3> | | ⊙ | | | | |
| Medium low | <0.1,0.3,0.5> | | | | | | |
| Medium | <0.3,0.5,0.7> | | | | | | |
| Medium high | <0.5,0.7,0.9> | | | | | | |
| High | <0.7,0.9,1.0> | ⊙ | | | | ⊙ | ⊙ |
| Very high | <0.9,1.0,1.0> | ⊗ | | ⊙ | ⊙ | | |

*Note: ⊗ decision maker 1; ⊙ decision maker 2.*

In this work, the preferences of two theoretical producers have been simulated trying to represent the most common viewpoints and interests of producers in respect to gilthead seabream and other species nowadays (see Table 7). For this reason, in contrast to the first decision-maker which is focused on maximizing the company's profits, the second one is more concerned about the impact of aquaculture production on the environment and the quality of the final product he offers to his customers, all of which without ignoring the economic aspects.

According to these opinions, the vectors of criteria weights for each decision maker are

$$\hat{w}_1 = (\langle 0.9, 1.0, 1.0\rangle, \langle 0.0, 0.0, 0.1\rangle, \langle 0.0, 0.0, 0.1\rangle, \langle 0.0, 0.0, 0.1\rangle, \langle 0.0, 0.0, 0.1\rangle, \langle 0.0, 0.0, 0.1\rangle)$$

$$\hat{w}_2 = (\langle 0.7, 0.9, 1.0\rangle, \langle 0.0, 0.1, 0.3\rangle, \langle 0.9, 1.0, 1.0\rangle, \langle 0.9, 1.0, 1.0\rangle, \langle 0.7, 0.9, 1.0\rangle, \langle 0.7, 0.9, 1.0\rangle)$$

Vector of criteria weights $\hat{\mathbf{w}}$ and matrix $\hat{\mathbf{X}}$ are used to construct the fuzzy weighted normalized decision matrices that can be seen in Table 8.

*Table 8. Weighted fuzzy rating matrix after normalization.*

| Decision maker 1 | | | | | | |
|---|---|---|---|---|---|---|
| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ |
| $F_1$ | <0.83,0.93,0.93> | <0.00,0.00,0.10> | <0.00,0.00,0.09> | <0.00,0.00,0.05> | <0.00,0.00,0.05> | <0.00,0.00,0.05> |
| $F_2$ | <0.90,1.00,1.00> | <0.00,0.00,0.07> | <0.00,0.00,0.09> | <0.00,0.00,0.10> | <0.00,0.00,0.05> | <0.00,0.00,0.07> |
| $F_3$ | <0.75,0.84,0.84> | <0.00,0.00,0.05> | <0.00,0.00,0.10> | <0.00,0.00,0.06> | <0.00,0.00,0.10> | <0.00,0.00,0.10> |
| Decision maker 2 | | | | | | |
| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ |
| $F_1$ | <0.65,0.83,0.93> | <0.00,0.10,0.30> | <0.65,0.79,0.88> | <0.35,0.43,0.48> | <0.35,0.45,0.50> | <0.32,0.41,0.45> |
| $F_2$ | <0.70,0.90,1.00> | <0.00,0.07,0.20> | <0.69,0.84,0.93> | <0.75,0.91,1.00> | <0.35,0.45,0.50> | <0.48,0.62,0.69> |
| $F_3$ | <0.59,0.75,0.84> | <0.00,0.05,0.15> | <0.76,0.93,1.00> | <0.49,0.61,0.65> | <0.70,0.90,1.00> | <0.70,0.90,1.00> |

### 5.5.4. Final decision

Once the matrices have been created, they allow us to calculate the distance of each alternative from the fuzzy positive ideal and anti-ideal solutions, and calculate the closeness coefficient of each alternative; the results are shown in Table 9.

As can be observed, in the case of the decision-maker with more concern for the economical profit, the model proposes the use of feed 2. This result agreed with the classic economic theory about profit maximization and the decision that was taken using only the fuzzy pay-off method.

However, when the decision-maker also expresses concern about the environmental and quality factors (decision-maker 2), the suggestion of the model is the organic/ecologic production. This concurs with the findings of some of the studies cited above about the importance of considering these new criteria reflecting the changing situation in the market and the most current demands and principles based on sustainability.

*Table 9. Results of TOPSIS method.*

| Decision maker 1 | | | | |
|---|---|---|---|---|
| Alternative | Distance from ideal | Distance from anti-ideal | Closeness coefficient | Ranking |
| $F_1$ | 2.218561 | 3.875127 | 0.635925 | 2 |
| $F_2$ | 2.169581 | 3.952186 | 0.645596 | 1 |
| $F_3$ | 2.254245 | 3.856005 | 0.631072 | 3 |

| Decision maker 2 | | | | |
|---|---|---|---|---|
| Alternative | Distance from ideal | Distance from anti-ideal | Closeness coefficient | Ranking |
| $F_1$ | 2.791154 | 3.351400 | 0.545604 | 2 |
| $F_2$ | 3.001972 | 3.193440 | 0.515452 | 3 |
| $F_3$ | 2.239739 | 3.986385 | 0.640268 | 1 |

## 5.6. Discussion and conclusions

Aquaculture is an economic activity that has grown exponentially in recent years thanks to the industrialization of production processes. The development of new technologies and the increase in the average size of companies has led to the increasing complexity of managing this activity. In addition, it is necessary to mention that the increase in production and trade, together with new patterns of consumption and social demands, have caused a greater competition. Furthermore, these changes in consumer behavior means that production strategies should not only consider profit maximization, but also sometimes meet certain environmental and quality criteria.

In this new context, the profit margin is increasingly tight, and the work of managers is more crucial than ever. The level of uncertainty of the results of the production strategies is not only conditioned by the high number of factors that affect production, but also by an increase in the volatility of those that are beyond the control of the managers.

These considerations have led many producers to become aware of the fact that they need the most advanced and appropriate expert systems to support their decision-making processes. Furthermore, those systems must have the capacity to deal with growing data volumes and have to be adaptable to new cultural contexts and for new purposes. In this regard, the results of the simulations carried out seem to confirm the goodness of the fuzzy methodologies for the determination of farming strategies in aquaculture farms in situations of uncertainty.

In this way, the methodology developed has proven to be a good alternative to take into account the risk or uncertainty when assessing the possible performance of the different production alternatives. Thus, it enables the decision-makers to consider three possible scenarios, the most possible one based on historical data and two extreme scenarios due to possible fluctuations in factors such as the water temperature, the market price or the customer valuation of new products. Furthermore, the fuzzy TOPSIS methodology has shown its great value in facilitating the assessment of the importance of each criterion by the producers through qualitative assessments.

All this does constitute substantial progress to meet specific needs or gaps in the development of OR models in aquaculture that consider simultaneously all aspects of long-term sustainability (Peñalosa et al., 2019). In addition, the development of this methodology also has significant implications in practice for both producers and regulators.

The importance of this approach to the aquaculture stakeholders has also been directly reflected in the results obtained, due to the crucial effect that the consideration of different scenarios has had in the decisions recommended to the company. In this regard, although the traditional methods that only take into account the economic profitability would recommend the first alternative (Table 5), which achieved a Net Present Value in the most likely scenario of about a 5%-40% increase, the consideration of the current uncertainty makes it inadvisable, due to the high volatility of its NPV ranging from about -358 to 6,716 USD. In that case, the second alternative stands out at the other extreme, with a NPV ranging from 2,683 to 6,470, which makes it more appropriate for risk-averse producers. In this way, the utilization of this methodologies allows aquaculture producers to accurately address the increasing uncertainty in their decision-making process which is a pressing need for the sector (Llorente and Luna, 2015).

The integration of multiple subjective and, sometimes, opposed criteria has also proven to give a greater degree of flexibility to decision making methodologies. In fact, this has sometimes led to a change in the optimal choice to another alternative that, despite not being the most appropriate in a goal, presents good overall results, as is the case of the second decision maker (Table 9). This responds to the actual need in aquaculture of combining complex optimization methods and multiple-criteria decision-making techniques in order to be able to make better decisions (Domínguez-May et al., 2020).

Furthermore, the application and testing of this method also constitutes a contribution to the discussion about the capacity of producers to move towards new forms of production without assuming too much risk. In this respect, the utilization of this type of methodology has proven that if the regulators are capable of determining objective criteria that enables producers to discern that they need to adopt new forms of production, the producers will be able to carry out effective strategic plans that reduce the risk. In this way, some institutions, such as FAO (2018b), have already highlighted this need for the different stakeholders (i.e. producers, governments and consumers) to look closely at production practices in order to bring them closer to a sustainable path.

Lastly, it should be noted that the application of these techniques is highly dependent on data. For that reason, the collection of reliable data, throughout real intelligent sensors and control systems, and the determination of objective indicators, are crucial factors in enhancing its effectiveness and efficiency. All this points out to the two lines of research, data collection and OR models, that would lead aquaculture farms to be data driven companies.

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# Capítulo 6

## *Transferencia del conocimiento Aplicación de ayuda a la toma de decisiones*

En el marco del proyecto europeo H2020 MedAID se han utilizado las metodologías desarrolladas a lo largo de esta Tesis Doctoral para el desarrollo de una herramienta abierta de planificación de la producción para empresas de acuicultura marina (AquiAID - Artificial Intelligence Decisions in Aquaculture).

De esta forma, como parte del trabajo de investigación llevado a cabo, se aborda uno de los puntos críticos en la generación de conocimiento, la transferencia y la explotación de los resultados.

Este desarrollo continúa con el objetivo planteado en esta investigación de abordar el proceso de toma de decisiones y planificación, estratégica y operativa, en empresas de acuicultura para la producción de pescado de forma eficiente. Además, dicha herramienta prioriza la usabilidad de las metodologías desarrolladas por parte de los distintos agentes del sector acuícola (productores, reguladores, investigadores…etc.) con el objetivo de concienciar acerca de la utilidad del empleo de las nuevas tecnologías y la inteligencia artificial para los tomadores de decisión, visualizando su influencia en la competitividad de las empresas. Esto podría suponer también un efecto positivo, aunque en un plazo más largo, sobre el sector acuícola a la hora de asignar recursos a los proyectos de desarrollo o aplicación de nuevos avances.

Con este fin, la herramienta se ha desarrollado en forma de aplicación web que combina el lenguaje HTML, la programación de las metodologías en código PYTHON y la conectividad con bases de datos MySQL, para proporcionar un acceso rápido y fácil a los usuarios.

Esto permite que cualquier agente interesado pueda utilizar el siguiente enlace para acceder a la aplicación web o consultar el manual de usuario:

http://www.ides.unican.es/aquiaid-2/

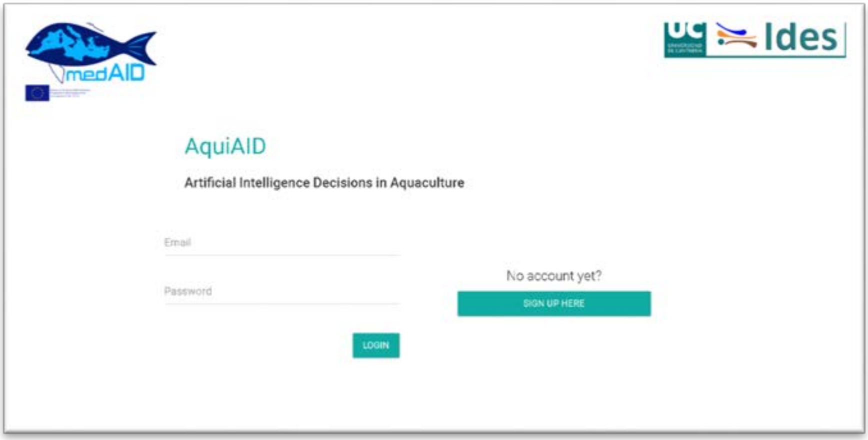



Fig 1. Aplicación Aqui AID

En cuanto a la eficacia de esta aplicación, radica en permitir a los usuarios la valoración de un gran número de alternativas y obtener resultados útiles, utilizando una interfaz sencilla y empleando un tiempo de computación reducido. Sin embargo, como se ha explicado anteriormente, la simulación y optimización de la actividad productiva y los procesos de toma de decisiones en acuicultura requiere de la integración de metodologías especialmente complejas, lo que dificulta esa tarea. Esto supone una de las dificultades más comunes de este tipo de herramientas, que permiten a especialistas en el sector, que no son expertos en tecnología, el aprovechar estas innovaciones a través de una interfaz simple. Para ello, dichas herramientas deben proporcionar una representación simplificada de los modelos y sus resultados, para que sean al mismo tiempo comprensibles para los decisores y lo suficientemente avanzadas para ser de utilidad.

Por estas razones, el trabajo llevado a cabo se ha centrado en la accesibilidad y usabilidad de dichos métodos. De esta forma, el desarrollo de esta herramienta y su aplicación han implicado la fijación de una serie de hipótesis de partida que simplifican su uso y la división del proceso en tres módulos que pueden ser gestionados de manera sencilla desde la pantalla principal:

- Introducción de datos: Cada decisor tiene a su disposición un método para adaptar los resultados a sus propios datos con respecto no solo a los factores internos y externos que tienen una influencia considerable en los procesos de producción de la granja, sino también a las preferencias y objetivos de los decisores. En caso contrario, la aplicación dispone de una serie de datos por defecto que facilitan su uso.

- Simulación: El proceso de simulación es capaz de estimar los resultados económicos, medioambientales y de calidad considerando los datos del productor en un caso básico. Ello permite visualizar los resultados de la explotación en el caso de no llevar a cabo estrategias complejas.
- Optimización: Por último, es posible realizar un proceso de búsqueda de la estrategia de producción óptima para cada unidad de producción. Para ello, se requiere de nuevo la selección de un horizonte de tiempo y el número máximo de lotes que se busca realizar durante ese tiempo.

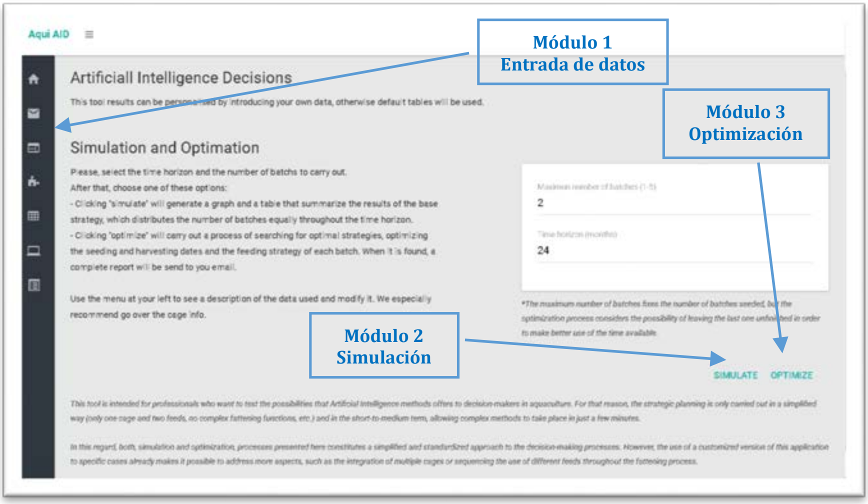
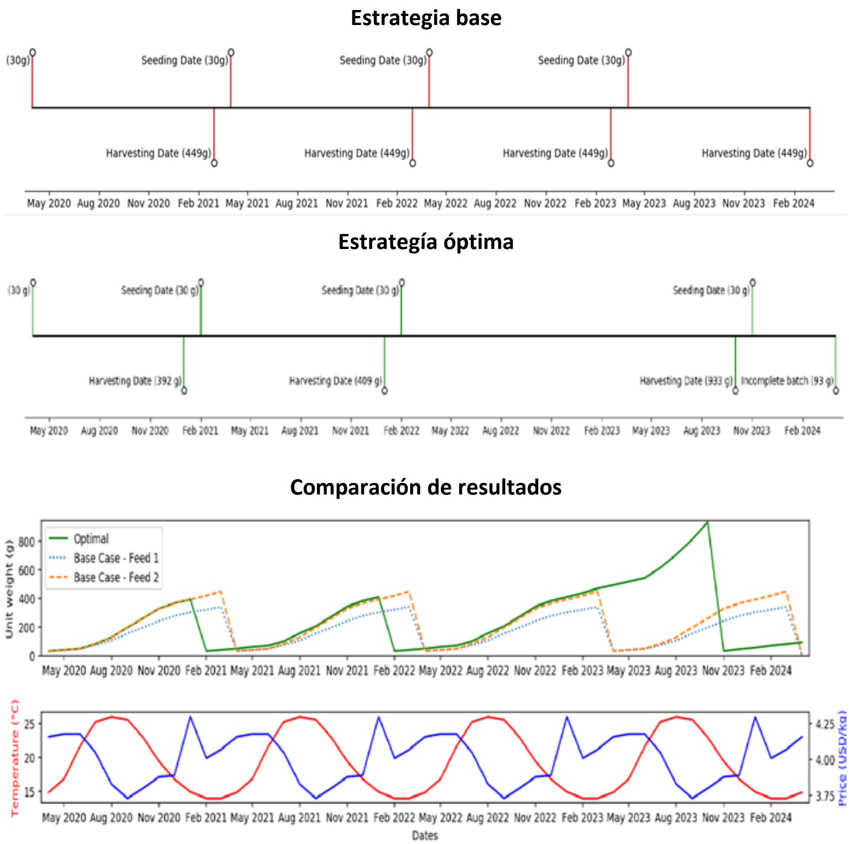



Fig. 2. Pantalla principal de la aplicación

Estos módulos permiten obtener la estrategia de producción más cercana al punto óptimo, la cual se proporciona al usuario como una recomendación que facilita el proceso de toma de decisiones de su compañía. Con este fin, la aplicación realiza el proceso de optimización para encontrar una alternativa de producción que mejore los resultados de la compañía tanto como sea posible, teniendo en cuenta los datos y parámetros de ejecución introducidos, además de un proceso de comunicación de los resultados. Todo esto requiere el uso de metodologías complejas y un tiempo de computación de unos minutos por lo que, para evitar esperas innecesarias, el proceso finaliza con la generación de una hoja de cálculo en Excel que se envía de forma automática al correo electrónico del usuario.

De esta forma es posible generar un informe muy completo que detalla la estrategia recomendada, presentando sus resultados de forma desagregada. Además, se lleva a cabo un proceso de visualización de los resultados (Figura 3) que garantiza que los usuarios tengan rápidamente.




| Criteria | Optimal | Base Case 1 | Base Case 2 |
|---|---|---|---|
| Operational Profit (€) | 38,073 | 15,032 | 25,440 |
| Organic Feeding | 100% | 0% | 100% |
| Efficiency (Fish in-Fish out) | 0.94 | 0.44 | 0.88 |
| Residues (g) | 1,687,838 | 1,070,650 | 1,586,814 |
| GWP (kg CO2 equiv.) | 24,629 | 17,121 | 23,155 |
| Fish Protein | 55% | 25% | 55% |
| Omega 3 Transmission | 2% | 1% | 2% |

Fig 3. Representación gráfica de los resultados

# Capítulo 7

## *Principales resultados y conclusiones del trabajo.*

A lo largo de las últimas décadas, la acuicultura ha experimentado el mayor crecimiento de su historia, lo que la ha llevado a convertirse en una industria relevante en el sector agroalimentario que, ante las restricciones que sufre la pesca a la hora de garantizar la sostenibilidad de los recursos, está llamada a satisfacer la demanda mundial de pescado, tal como sucedió con la ganadería y la caza hace siglos. Este crecimiento no habría sido posible sin el desarrollo de innovaciones tecnológicas, las cuales han conseguido transformar la industria desde los sistemas extensivos tradicionales a los novedosos métodos de producción intensiva, generando ventajas a largo plazo en términos de productividad y eficiencia en la producción. Sin embargo, en lo que se refiere a la gestión de empresas, el avance de la industria acuícola ha sido más lento de lo esperado debido a la compleja interacción de factores de distinta naturaleza y a la dificultad de las empresas para desarrollar y aplicar tecnología específica que solucione sus principales problemas.

Actualmente, uno de los mayores desafíos a los que se enfrenta el sector de la acuicultura es el cambio en los patrones de producción y consumo de pescado. Por un lado, el consumo de pescado ha crecido significativamente, pero, a su vez, las exigencias de los consumidores y la competencia entre empresas son cada vez mayores. Por este motivo, la calidad del producto además de sus efectos sobre el medioambiente y la salud son cada vez aspectos a tener más en cuenta, sin olvidar la importancia del precio de venta. Todo esto, ha tenido un impacto directo sobre la complejidad de los procesos de toma de decisiones en las empresas, que deben integrar los objetivos económicos tradicionales con el uso eficiente de los recursos naturales y las preferencias de los consumidores.

En este contexto, la dificultad para satisfacer las nuevas demandas sin sufrir una pérdida de rentabilidad, junto con las nuevas posibilidades que aportan las innovaciones en los sistemas de producción, ha propiciado un gran número de procesos de fusión y adquisición entre empresas y un mayor esfuerzo en la diversificación de productos con el fin de obtener una ventaja de las economías de escala y alcance generadas. Esto ha llevado también a una planificación de la producción más detallada, anticipando la planificación de los siguientes años y teniendo en cuenta las restricciones e interrelaciones entre las, cada vez más, unidades productivas de la empresa. Ello supone un aumento exponencial de la complejidad en el proceso de toma de decisiones, tanto por el número de factores a tener en cuenta como por la cantidad de posibles estrategias.

Por todas estas razones, la necesidad de desarrollar sistemas de gestión más eficientes para apoyar a los directivos en la toma de las principales decisiones estratégicas y operativas de la empresa es cada vez más grande. A lo largo de los últimos años, se han llevado a cabo diversos trabajos de investigación para el desarrollo de modelos, herramientas de gestión y sistemas de ayuda a la toma de decisiones (DSS). Sin embargo, los métodos de análisis y optimización tradicionales no son lo suficientemente potentes para abordar la complejidad existente, por lo que se requiere del desarrollo de técnicas que permitan el análisis de grandes volúmenes de datos (Big Data) y nuevas herramientas o modelos de optimización apoyados en la Inteligencia Artificial (IA).

Como respuesta ante esta situación, el objetivo de esta tesis ha sido el análisis del proceso de toma de decisiones en las empresas de acuicultura y el desarrollo de nuevas metodologías que permitan su optimización, incrementando así la eficiencia de los sistemas de gestión actuales y permitiendo su aplicación práctica en el contexto actual. La consecución de este objetivo ha requerido la aplicación de distintas técnicas de simulación, Inteligencia Artificial y optimización para dar una respuesta efectiva a la complejidad existente en el sector.

A continuación, siguiendo el orden de los objetivos específicos propuestos inicialmente, se presenta un resumen de los principales resultados obtenidos y las conclusiones más importantes a las se ha llegado para cada uno de ellos.

1. El análisis y los resultados obtenidos en la línea de trabajo marcada por el primer objetivo, "Estudiar la situación actual de las empresas del sector acuícola, los problemas de mayor importancia a los que se enfrentan y las alternativas de las que disponen", han servido como punto de inicio para esta tesis:

   El proyecto MedAID, en el cual se circunscribe esta tesis, tiene entre sus objetivos el análisis los resultados de las empresas del sector acuícola, el desarrollo de metodologías que permitan optimizar dichos resultados y la cuantificación del impacto económico de las innovaciones que se lleven a cabo en el sector. Como se explica en el apartado 1.4.1, en la realización de ese proceso se observó una fuerte volatilidad en los resultados de las empresas, lo que ha propiciado frecuentes crisis en el sector, y especialmente en las empresas de producción de dorada y lubina, especies en la que se focalizan las aplicaciones empíricas de este trabajo.

   El origen de esos problemas en las empresas del sector se puede sintetizar en tres fuentes: la complejidad de las decisiones de producción generada por la interacción de factores económicos, biológicos, tecnológicos y medioambientales que intervienen en sus procesos; los desajustes en el mercado de productos acuícolas debidos a las distorsiones que genera la estacionalidad de la producción junto con la entrada de nuevos competidores fruto de la globalización y, por último, la dificultad para incorporar las innovaciones por parte de las empresas cuya escala y capacidad de gestión no son las adecuadas.

A partir del análisis de estos problemas es posible llegar a la siguiente conclusión, que es a la vez la principal motivación para la realización de esta Tesis Doctoral y una de las demandas más comunes de las empresas acuícolas. El avance eficiente y sostenible de la acuicultura depende en gran medida del desarrollo de metodologías que permitan abordar el proceso de toma de decisiones de forma integral, es decir, desde el comienzo de la actividad productiva hasta el momento de venta de los productos finales, priorizando la flexibilidad de los procesos para adaptarse a nuevos objetivos.

2. El trabajo realizado para alcanzar el segundo objetivo, centrado en “Identificar los principales criterios influyentes en el proceso de toma de decisiones en acuicultura y las necesidades de datos, incluyendo las posibles fuentes de información, tanto cuando se consideran fines puramente económicos, como cuando se plantean nuevas formas de producción como, por ejemplo, la producción sostenible”, nos ha permitido llegar a las siguientes conclusiones:

A lo largo de esta Tesis Doctoral se prioriza la construcción de modelos que incluyan las principales variables que inciden en el resultado de las empresas y los criterios a seguir en el proceso de toma de decisiones. Para la realización de este trabajo se ha tratado de secuenciar dicho proceso, comenzando por la exploración de los objetivos de las empresas y su integración en modelos de optimización sencillos para, después, ir incorporando mayor complejidad y, con ello, realismo y aplicabilidad a dichos modelos.

Hoy en día, cada vez es más habitual encontrar empresas que no solo están preocupadas por la minimización del coste, como se pensaba en la teoría económica clásica, sino que tratan de dar respuesta a las demandas de los consumidores en términos de producción sostenible o calidad de producto, a través de nuevas formas de producción. En este nuevo contexto, como se ha explicado en el capítulo 2, se han identificado 9 criterios principales que dirigen el proceso de toma de decisiones en acuicultura, los cuales pueden ser clasificados en tres grupos: criterios económicos, criterios medioambientales y criterios de calidad del producto.

La primera conclusión tras la identificación de estas variables influyentes, ha sido la existencia de una laguna en los modelos y sistemas de gestión desarrollados en acuicultura, dado que las variables relacionadas con las nuevas formas de producción son raramente tenidas en cuenta. Esta limitación no se debe a la falta de interés de los productores, que son conscientes del impacto ambiental de su actividad, ni de los consumidores y la sociedad en general, entre los cuales existe una conciencia cada vez mayor. Sin embargo, los aspectos medioambientales y de calidad no se habían considerado adecuadamente por la comunidad científica hasta hace pocos años, provocando una falta de metodologías que permitan incluir dichos criterios en la planificación de la producción de manera eficiente, lo que constituye una barrera para el desarrollo de nuevas alternativas de producción.

Por otro lado, uno de los hallazgos de investigación más llamativos de este punto ha sido la baja utilización de indicadores de producción sostenible, como la huella de carbono o el tratamiento de desechos, en las certificaciones de productos orgánicos reguladas de forma privada o por la legislación de la UE. De esta forma, mientras que estos productos se identifican en el mercado como productos ecológicos, algunos carecen de eficiencia en la generación de desechos o contaminantes, incluso presentando resultados significativamente peores. Esto sugiere que puede existir una confusión, tanto para productores como para los consumidores, a la hora de distinguir entre una producción orgánica y una producción medioambientalmente sostenible, lo que coincide con la conclusión señalada en diversos artículos, como el realizado por Madin y Macreadie (2015).

3. El trabajo realizado en torno al tercer objetivo para "Determinar el método más adecuado para integrar dichos criterios en una única función objetivo que permita cuantificar el efecto de las distintas estrategias de producción sobre los resultados de la empresa y pueda ser utilizada como objetivo de optimización" nos ha llevado a los siguientes resultados y conclusiones:

La identificación de las limitaciones de los sistemas de gestión utilizados en las empresas de acuicultura para integrar los distintos factores que inciden en la producción y comercialización de los productos, ha planteado una necesidad principal: El desarrollo de una metodología multicriterio de toma de decisiones (MCDM) que integre los factores de decisión en la función objetivo, basándose en las prioridades de cada empresa. Con esta finalidad, se ha utilizado la técnica AHP para medir de forma sencilla la importancia que el productor otorga a cada criterio y la técnica TOPSIS para desarrollar una función que mida el ajuste de los resultados de cada estrategia a la alternativa que sería ideal para dicho productor, procesos que vienen descritos con detalle en el capítulo 2 de esta Tesis Doctoral.

Como principal resultado, la metodología ha demostrado tener capacidad para la realización de un ranking de las estrategias más adecuadas para cada productor en diferentes escenarios, permitiendo considerar las demandas de los *stakeholders* en aspectos como la responsabilidad medioambiental, la calidad del producto y, por supuesto, la eficiencia económica. Esto supone una contribución novedosa para las empresas del sector y para la investigación de los efectos conjuntos de muchos de estos criterios, cuya necesidad ya había sido señalada directamente en estudios anteriores, como el desarrollado por Mathinsen (2016), que destacaban la ausencia de sistemas multicriterio bien documentados para la acuicultura.

En conclusión, la aplicación de esta metodología multicriterio a la toma de decisiones supone una contribución a la mejora de la eficiencia y la flexibilidad de los procesos de decisión. Primero, debido a que se ha mostrado muy eficiente a la hora de integrar en el objetivo de la empresa un gran número de criterios, a veces subjetivos u opuestos entre sí, superando así las restricciones de los sistemas clásicos que únicamente consideraban los aspectos económicos. Además, abre la puerta a la futura inclusión de nuevos criterios que hagan referencia a otras formas de producción, sin necesidad de hacer cambios en la metodología. Por otro lado, ha incrementado la flexibilidad de estos modelos al permitir la estimación de las preferencias de cada productor en cuanto a la selección de los criterios de decisión y su importancia relativa, lo que permite la aplicación de esta metodología en escenarios muy diversos, adaptándose tanto a escenarios que priorizan un solo aspecto como a otros más complejos. Por último, porque el desarrollo de una función objetivo multicriterio permite que esta metodología sea integrada en distintos modelos de optimización o sistemas de ayuda a la toma de decisiones, para abordar todo tipo de decisiones.

*4.* En cuanto al cuarto objetivo, en el que se busca "*Desarrollar una metodología que permita optimizar las decisiones de alimentación, las cuales son consideradas las decisiones más complejas e influyentes en los resultados de la empresa. Por esta razón, se analizan de forma aislada, sin tener en cuenta otras decisiones, para una única unidad productiva y un solo lote*", podemos concluir lo siguiente:

La estrategia de alimentación se podría definir como la determinación del pienso que ha de utilizarse durante el proceso de engorde en función de diferentes factores internos y externos. Tradicionalmente ésta era una decisión sencilla que se tomaba una vez para todo el proceso de engorde, pero, con la generalización de los cambios de pienso a lo largo del proceso para obtener mejores resultados, la complejidad del análisis se ha incrementado exponencialmente. Además, esta decisión es prioritaria para las empresas de acuicultura dado que la alimentación es el principal coste operativo y el factor más influye en el tiempo de engorde (rotación de la explotación) y en la calidad y sostenibilidad del producto. Sin embargo, los esfuerzos de investigación en relación a la alimentación se han centrado en abordar el problema desde el punto de vista del fabricante de pienso, es decir, analizando los ingredientes que formarían la formulación óptima del alimento, y no desde él del empresario como han constatado Kousoulaki et al. (2015) o Sørensen (2012).

En consecuencia, con el objetivo de abordar el problema desde una perspectiva general y optimizar el resultado del proceso de alimentación, se ha comenzado con la realización de un análisis de elección entre las alternativas de pienso existentes en el mercado (apartado 2.3) y, más tarde, se ha llevado a cabo un análisis de mayor complejidad que plantea la posibilidad de secuenciar el uso de diferentes piensos a lo largo del proceso productivo. Con este fin, se ha desarrollado una metodología de búsqueda a partir de un Algoritmo Genético, el cual permite generar alternativas que cada vez se adecuen más al objetivo de producción multicriterio (capitulo 3). Los resultados obtenidos han mostrado que dependiendo de las preferencias de cada productor la estrategia de alimentación que se debería llevar a cabo es muy distinta, y, además, que la secuenciación del uso de diferentes piensos, según las condiciones internas y externas, es una vía que produce una mejora significativa de los resultados de las empresas.

Estos resultados han permitido confirmar la validez de una estrategia de alimentación muy común en la práctica, sobre todo en localizaciones donde se produce una gran variación de la temperatura del agua, en la que los productores utilizan piensos específicos para invierno y verano, lo que les permite obtener mejores resultados. Por otro lado, es posible concluir que las técnicas metaheurísticas, como los Algoritmos Genéticos, son una solución adecuada para abordar problemas complejos de este tipo, ya que han demostrado ser consistentes en sus resultados y tener la suficiente capacidad para alcanzar los objetivos con un coste computacional (tiempo) bajo. Todo esto se traduce en una contribución a la mejora de la eficiencia y la flexibilidad de las decisiones de alimentación en acuicultura que abre la puerta a las nuevas formas de engorde sostenible.

5. El trabajo realizado con el objetivo de "Abordar la optimización del proceso de toma de decisiones de forma completa, es decir, integrando las principales decisiones como parte de un proceso conjunto a largo plazo que considere múltiples unidades de producción (jaulas) y lotes, manteniendo el enfoque de objetivo multicriterio" nos ha llevado a obtener las siguientes conclusiones:

Como se ha explicado anteriormente, el análisis de las principales decisiones de producción de forma aislada no es suficiente para mejorar la eficiencia de los sistemas de gestión en acuicultura, puesto que la optimización de los objetivos requiere que las decisiones sean tomadas teniendo en cuenta el efecto conjunto que provocan en las diferentes estrategias y unidades productivas. Por esta razón, esta investigación se ha marcado como objetivo más importante abordar el proceso de toma de decisiones de forma integral, considerando sus principales decisiones, como son la especie y peso de los alevines con el que se introducen en las jaulas, la estrategia de alimentación y las fechas de siembra y despesque; como parte de un conjunto con múltiples unidades de producción (jaulas) y en un horizonte temporal a largo plazo (múltiples lotes).

La complejidad de este objetivo requiere de técnicas de optimización más avanzadas por lo que se ha aplicado una técnica metaheurística de optimización, *Particle Swarm Optimization*, que simula el comportamiento social de enjambres que guían a sus miembros de forma inteligente para buscar en las regiones más prometedoras del espacio de búsqueda (Eberhart y Kennedy, 1995). Los resultados obtenidos han corroborado la capacidad de esta técnica para tratar de manera eficiente los problemas de optimización complejos consiguiendo encontrar soluciones cercanas al óptimo en diferentes escenarios. Esta metodología, una vez implementada en un sistema que facilite su usabilidad, permite responder a la necesidad de apoyo al proceso de decisión de las empresas de acuicultura, que cada vez tienen una escala mayor, debida al proceso de concentración del sector, y mayores exigencias de eficiencia consecuencia del incremento de la competencia.

En este sentido, es posible concluir que esta metodología es capaz de generar un efecto positivo en la posición competitiva de la empresa en el mercado acuícola por varios motivos. En primer lugar, permite mejorar la capacidad de gestión de los productores acuícolas, diseñando una planificación estratégica en la que interactúan las principales variables que condicionan el margen de cría, superando así las principales restricciones de investigaciones anteriores. Por otro lado, esta metodología permite considerar nuevas formas de producción dentro de la empresa lo que mejoraría sustancialmente la capacidad de la empresa para enfrentarse a las demandas de los agentes con intereses en la acuicultura o reducir su riesgo a través de la diversificación. Además, cualquier esfuerzo dirigido a aumentar el registro de información y la transparencia, revertiría directamente en una mejora de la capacidad del modelo para maximizar los resultados de la empresa.

6. En cuanto al sexto objetivo, “Evaluar los efectos de la inclusión de restricciones complejas propias del negocio, ya sean operativas o comerciales, en el proceso de

toma de decisiones; tanto desde el punto de vista de la eficiencia computacional de las metodologías desarrolladas, como de la utilidad y resultados de la decisión finalmente tomada", el trabajo realizado ha permitido obtener las siguientes conclusiones acerca de la capacidad de adaptación de los modelos desarrollados a situaciones reales más complejas:

Como parte del proceso de investigación necesario para el desarrollo de una metodología que modele el desempeño de las empresas de acuicultura en función a diversos factores y permita optimizar su proceso de toma de decisiones, es necesario examinar la capacidad de dicha metodología para abordar los procesos más complejos que la acerquen a la realidad del sector. Uno de ellos es la posibilidad de incorporar restricciones específicas de la empresa que modificarían de forma sustancial la estrategia óptima, ya que los modelos y metodologías que no incorporan dichas restricciones, en aras a reducir la complejidad, han demostrado ser poco realistas y difícilmente aplicables a la práctica del sector acuícola. Esto se debe a que esta situación es muy común en un sector que acostumbra a presentar restricciones operativas (cuánto se puede despescar y procesar en un momento dado, debido a limitaciones laborales o físicas) y comerciales (cantidad mínima o máxima a comercializar en un periodo de tiempo) que rara vez son incorporadas a los sistemas de gestión.

Tal y como se esperaba, la inclusión de esas restricciones múltiples y complejas ha conllevado un aumento de la complejidad que la metodología de optimización debe enfrentar y también cambios en los resultados obtenidos y el coste computacional del proceso. Sin embargo, esto no ha reducido la capacidad de la metodología desarrollada para obtener resultados positivos para la empresa. Las restricciones operativas, han llevado a la obtención de estrategias más realistas, donde el productor tiene que secuenciar las operaciones realizadas por su personal. Por otro lado, la inclusión de diversos acuerdos comerciales en fechas específicas ha mostrado un efecto importante en las decisiones de la compañía. En este sentido, es posible determinar cómo incide en la planificación de la empresa la necesidad de responder a ellos y, lo que es más importante, como afectan a la creación de valor y la reducción del riesgo, con el objetivo de valorar si este tipo de acuerdos aportan valor para el empresario.

En cuanto al coste computacional del proceso, se ha llevado a cabo un proceso de evaluación y discusión de la forma más adecuada para abordar la inclusión de estas restricciones. En primer lugar, este proceso nos ha llevado a concluir que se debe incrementar el espacio de búsqueda que es cubierto por la metodología, por la existencia de áreas que no cumplen las nuevas restricciones, sin reducir demasiado la eficiencia de la metodología. Para ello, se ha optado por incrementar el número de partículas utilizadas y mantener el número de movimientos que estas realizan. Además, se ha concluido que la utilización de una función de penalización no estacionaria o dinámica, que penaliza el resultado de ajuste de la estrategia por cada restricción no cumplida, permite mejorar, en velocidad y calidad, el proceso de búsqueda de soluciones es la alternativa que mejores resultados consigue, como ya había concluido el estudio realizado por Parsopoulos and Vrahatis (2002a) para otros casos.

7. Por último, a la hora de "Valorar la utilización de modelos computacionales que permitan considerar la incertidumbre e imprecisión respecto a la evolución de algunos factores, dejando atrás los modelos deterministas tradicionales", se han obtenido las siguientes conclusiones sobre la capacidad de adaptación de los modelos desarrollados a situaciones reales más complejas:

Otra de las limitaciones detectadas en los modelos de apoyo a la toma de decisiones es que, a pesar de incluir cada vez un número mayor de factores, no se considera la incertidumbre existente en torno a ellos. Esto se debe a que los modelos tradicionales abordan los procesos de planificación desde un punto de vista determinista, lo que dificulta su aplicación a la práctica de un sector en el que el riesgo es alto. Para evitar esto se debe tener en cuenta la volatilidad de todos los factores que condicionan la producción de la empresa y están fuera del control de los decisores.

Por esta razón, una vez desarrollados los nuevos modelos, se ha avanzado en la utilización de modelos probabilísticos que permitan considerar, al menos en parte, dicha incertidumbre. Para ello se han utilizado dos metodologías que han demostrado ser de gran utilidad. El primer método, llamado fuzzy pay-off, ha permitido evaluar la rentabilidad económica de cada estrategia considerando tres escenarios posibles, el escenario esperado basado en datos históricos y dos escenarios extremos debido a posibles fluctuaciones en factores como la temperatura del agua, el precio de mercado o la valoración del cliente de los productos de la empresa. En segundo lugar, se ha utilizado la metodología TOPSIS difusa que ha demostrado su utilidad para integrar el uso de múltiples criterios subjetivos y, a veces, opuestos y sus diferentes escenarios de evolución posibles.

Los resultados obtenidos en las distintas simulaciones realizadas han confirmado la capacidad de las metodologías difusas para la selección de estrategias de producción acuícola en situaciones de incertidumbre. La importancia de este enfoque se ha reflejado principalmente en los escenarios de gran incertidumbre en los cuales la alternativa que presentaba un beneficio más alto también estaba expuesta a un elevado riesgo, por lo que la metodología desarrollada recomendaba la utilización de otra estrategia que a la postre presentaría una mejor relación rentabilidad-riesgo. Por último, esta metodología ha mostrado implicaciones significativas en la práctica tanto para los productores como para los reguladores, ya que constituye una contribución a la discusión sobre la capacidad de los productores para avanzar hacia nuevas formas de producción sin asumir más riesgo del deseado.

Por último, es necesario destacar una de las principales conclusiones extraídas a lo largo de todo el trabajo realizado y es que la transferencia del conocimiento al sector, de forma rápida y fácilmente aplicable es vital para el avance de este. De esta forma se permite que usuarios no expertos en las áreas de investigación de esta Tesis Doctoral, que en este campo son la mayoría, den respuesta a los problemas actuales y, al mismo tiempo, se conciencien de la necesidad de futuros avances en esta misma línea.

# Capítulo 8

## *Futuras líneas de investigación*

En cuanto a las futuras líneas de investigación, la prioridad es continuar con el desarrollo de una metodología que integre todos los avances, permitiendo así dar respuesta a los problemas del sector en conjunto. En este sentido, destaca la utilización de modelos computacionales en torno a todos los factores de riesgo para tener en cuenta la posible volatilidad de los resultados y, además, la mayor adaptación de los modelos a las características específicas de la empresa en cuanto al números de unidades productivas, piensos disponibles y restricciones comerciales y operativas, supeditando el proceso de decisión a las prioridades del agente.

Esto requiere también la mejora de las técnicas de optimización tanto por su capacidad para encontrar la alternativa óptima, como por la velocidad a la hora de hacerlo. En este sentido, se requiere la utilización de ordenadores con una capacidad de computación más alta, supercomputadoras, para validar los modelos y determinar la combinación adecuada de parámetros de optimización que incrementan la eficiencia y la aplicabilidad de estas metodologías en la práctica. Esto requeriría una optimización conjunta de todos ellos y la introducción de parámetros dinámicos o autoadaptativos, que han demostrado ser una opción que mejora esta tediosa tarea de pre-procesamiento para el ajuste de los parámetros.

Una vez más, es necesario destacar la necesidad de trabajar en la comunicación y la transferencia del conocimiento al sector, procurando reducir la tradicional distancia que hay entre los científicos y los empresarios. Para ello, es prioritario fomentar la colaboración y, también, utilizare canales de divulgación más próximos al sector que las publicaciones científicas. En esta línea, es vital el desarrollo de sistemas de apoyo a la toma de decisiones que sean flexibles, accesibles y, sobre todo, que posibiliten la interacción del sector, algo que ya se ha conseguido en buena medida en el ámbito biológico.

Por último, a lo largo de esta Tesis Doctoral se han destacado una serie de aspectos que, más allá de las nuevas líneas de investigación, mejorarían los resultados de las metodologías desarrolladas en la actualidad. En primer lugar, es necesario incrementar la calidad de los datos recopilados y los indicadores utilizados para medir de forma adecuada el impacto de algunas decisiones. Este es un hecho diferencial en el desarrollo de nuevas metodologías basadas en el uso de las técnicas de Inteligencia Artificial que son altamente dependientes de los datos, más aún en un sector como el acuícola en el que intervienen un gran número de factores. Por otro lado, es necesario seguir avanzando en la integración de los aspectos principales de la producción ecológica y sostenible con los tradicionales factores económicos de la empresa tanto con la realización de modelos teóricos como con la implementación de estos en la práctica.

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# Anexo

## *Índice de tablas y figuras*

## I. Índice de Figuras

## II. Índice de Tablas