DEXiAqua, a Model to Assess the Sustainability of Aquaculture Systems: Methodological Development and Application to a French Salmon Farm

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Samuel Le Féon [1,*], Théo Dubois [2], Christophe Jaeger [2], Aurélie Wilfart [2], Nouraya Akkal-Corfini [2], Jacopo Bacenetti [3], Michele Costantini [3] and Joël Aubin [2,*]

[1] Independent Researcher in Environmental Assessment, Pépinière ESS, 23 rue des Chênes, 35630 Langouët, France
[2] UMR SAS, INRAE, Institut Agro, 35000 Rennes, France; dubois.theo1@outlook.fr (T.D.); christophe.jaeger@inrae.fr (C.J.); aurelie.wilfart@inrae.fr (A.W.); nouraya.akkal-corfini@inrae.fr (N.A.-C.)
[3] Department of Environmental Science and Policy, Università degli Studi di Milano, Via Giovanni Celoria 2, 20133 Milan, Italy; jacopo.bacenetti@unimi.it (J.B.); michele.costantini@unimi.it (M.C.)
* Correspondence: samuel.lefeon@gmail.com (S.L.F.); joel.aubin@inrae.fr (J.A.)

Abstract: Aquaculture is increasingly considered a major contributor to the growing demand for worldwide seafood production. Sustainability is becoming a key issue for aquaculture systems, with the objective to produce seafood with lower environmental impacts and that is economically viable and socially fair. In the context of the SIMTAP project, a multi-attribute model called DEXiAqua was developed. DEXiAqua uses the DEX method to assess the sustainability of aquaculture systems via indicators from technical domains and reference methods (i.e., life cycle assessment, life cycle costing, social life cycle assessment, and emergy accounting) selected and organized by the partners in the SIMTAP project. The DEX method consists of building an attribute tree that is organized to characterize a complex problem. Qualitative or quantitative indicators are measured at the end of each branch of the tree. The value of each indicator is translated into a qualitative scale for the associated attribute via threshold values. Weighted utility functions are used to build attributes from sub-attributes until the attribute of overall sustainability is reached. DEXiAqua was applied to a case study of salmon farming in France, which illustrated its ability to assess overall sustainability and help identify ways to improve the production system by identifying environmental, social, and economic hotspots. More case studies are required to apply DEXiAqua to a variety of systems with technical and contextual differences, which could result in changing attribute weights to adapt it better to different contexts.

Keywords: sustainability assessment; multicriteria decision analysis (MCDA); DEXi; aquaculture; life cycle; decision tool

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1. Introduction

In response to the growing world population, with 9 billion people estimated by 2050 [1], demand for seafood is expected to increase in the near future. The need for diverse protein sources is particularly at risk. From 1960 to 2010, the world demand for edible fish nearly doubled from 9.9 to 18.6 kg per capita per year, and it should continue to grow. Demand could reach 21.5 kg per capita per year by 2030 [2]. Fisheries catches have remained stable for ca. 10 years and do not seem sufficient to respond to this increase in demand. For decades, demand has been supplemented with aquaculture, whose production has increased by 7.5% per year since 1970 [2]. Current aquaculture systems are required to be more sustainable to better manage financial, technological, institutional, natural, and social resources [3].

Aquaculture has several direct effects, such as emission of fish farm waste (e.g., nitrogen, phosphorus) and potential effects on endemic species due to introducing non-native species or propagating diseases, and indirect effects related to the production of fish feed, all of which have an impact on the environment [4–7]. Aquaculture also depends greatly on fisheries since it is the largest consumer of fishmeal and fish oil. Ingredients from fisheries are critical since they provide polyunsaturated fatty acids and proteins with amino acid profiles suitable for fish growth. Alternative ingredients in feed have also been studied [8–13]. To be sustainable, aquaculture must improve socially and economically. Globally, labor rights violations that have been documented in the sector should be eradicated [2]. Europe should work to improve the situation, and relocating production could be part of the solution. Currently, 65% of fish consumed in Europe is imported, 25% comes from European Union (EU) fisheries, and only 10% is produced in EU aquaculture [2]. Aquaculture could also create employment. It is estimated that each percentage point increase in consumption of fish from aquaculture would create 3000–4000 full-time jobs [14]. Thus, the aquaculture sector is expected to increase production to sustain the increase in fish consumption by creating local jobs and, more generally, contributing to food security [2]. Consequently, aquaculture needs to change in order to grow.

Among the strategies for changing aquaculture systems, integrated multitrophic aquaculture (IMTA) goes further by associating complementary species in the same production system [15–17]. Different levels of the trophic chain are reared together to support each other's growth. Inorganic and organic waste from fed aquaculture species (e.g., finfish) are respectively assimilated by autotrophic species (e.g., phytoplankton, macroalgae, macrophytes) and heterotrophic species (e.g., oysters, mussels, crustaceans, echinoderms, polychaetes) that are co-cultured with the fed aquaculture species. Currently, the most common IMTA systems are aquaponic systems that use nutrients in the wastewater from fish to support plant growth [18]. More complex systems combine polychaete-assisted sand filters and halophyte aquaponics for super-intensive marine fish farms [19]. IMTA systems are designed as potential future solutions to decrease the impacts of fish production on ecosystems [20–22].

The SIMTAP project (EU PRIMA 2018) was launched in June 2019 with the objective of developing self-sufficient IMTA systems in several Mediterranean countries (France, Italy, Malta, and Turkey) to improve nutrient recycling. The project will also assess their sustainability performance. Assessment of food-system sustainability needs to consider multiple criteria and multidisciplinarity [23,24]. In this context, environmental, social, and economic impacts should be evaluated together. Assessing sustainability also depends on the context and the issues that impact those involved. Therefore, multiple stakeholders from the regions concerned need to participate, as shown previously in the aquaculture sector [25,26]. A relevant option to meet this objective involves using a multicriteria decision analysis (MCDA) method, which explicitly considers multiple criteria to help individuals or groups explore relevant decisions [27]. It can combine objective measurements and value judgments using quantitative or qualitative indicators, makes subjectivity explicit, and manages this subjectivity by organizing input from the stakeholders concerned. To help decision makers choose more sustainable options or scenarios, MCDA was chosen to combine the environmental, social, and economic dimensions into a method to assess overall sustainability. To simplify this complex and multidimensional issue, the DEXi method [28] was selected as the MCDA method. Among other methods [29], the DEXi method has been used successfully in the agriculture sector to build sustainable assessment tools and to summarize expert knowledge. The MASC model was developed and applied to evaluate the sustainability of cropping systems [30,31] and later included in the DEXiPM model [32–34] and the MASC-OF model that focuses on organic production [35]. The DEXiFruit model aims to assess the sustainability of fruit production [36]. DEXi was also used to assess the sustainability of potato production [37]. DEXi was also combined with FisPro to include fuzzy logic to assess sustainability [38]. DEXi was also used in agricultural systems to evaluate specific issues as soil quality [39] or ecological and economic impacts of genetically modified crops [40]. To our knowledge, it has not yet been applied to assess the sustainability of aquaculture systems. It was used to select marine fish for IMTA production in the context of the SIMTAP project [41].

This article presents the DEXi model, which was developed with information from working groups, meetings, and discussions among stakeholders involved in the SIMTAP project to obtain an operational model, called DEXiAqua, to assess the sustainability of aquaculture systems. In this study, the term "system" refers to different scales associated with the farm: the farm itself with all the processes and workforce involved in the production of aquatic products; the upstream processes associated with the production of inputs (e.g., feed, energy), when LCA impact categories are calculated; and the network of economic and social links, especially in the assessment of the social pillar. The main steps were to (i) build a conceptual model to describe the three dimensions of sustainability in aquaculture systems based on technical and scientific literature, which yielded an attribute tree, (ii) determine utility functions and weights used to aggregate the attributes, and (iii) determine thresholds to convert quantitative and/or qualitative values of indicators into scales for attributes (e.g., low/medium/high). A template for data collection was developed to collect the raw data necessary and calculate the indicators. An initial application of DEXiAqua is also shown to illustrate its outputs. Four results of the study are presented: (1) the building of DEXiAqua, including the attribute tree, scales, and thresholds; (2) the indicator values and attribute scales obtained from applying the data-collection template to the reference case study; (3) results of applying DEXiAqua to the reference case study, and (4) the sensitivity of DEXiAqua to input variables.

2. Materials and Methods

2.1. DEXi Methodology

DEXi is software that can simplify complex systems when making multi-attribute decisions (the latest version, DEXi 5.04, is available online [42]). It is specially designed for choosing among multiple options, scenarios, or systems by considering many parameters [28]. Briefly, it breaks down a multi-factorial problem into smaller sub-problems until it obtains several problems that are easier to solve. DEXi can then be used to evaluate different scenarios or options for a multi-factorial system and help make decisions. Designing a DEXi model requires multiple steps (Figure 1) [31]:

- Define attributes, each of which is a qualitative variable that represents a sub-problem. An attribute, sometimes called a criterion [25], corresponds to each node of the tree;
- Define scales, each of which contains a set of options defined for each attribute (e.g., [Low; Medium; High], [Acceptable; Not acceptable]);
- Define the attribute tree, which breaks the main problem down into sub-problems (branches);
- Define utility functions, which aggregate branches of the attribute tree from the bottom (i.e., sub-problems) to the top (the main problem) (e.g., IF sub-problem #11 is Low AND sub-problem #12 is High THEN problem #1 is Medium).

DEXi uses qualitative attributes that are aggregated and potentially weighted to obtain a final score. This approach allows quantitative and qualitative attributes (e.g., social issues) to be considered simultaneously.

Once the DEXi model is built, the next step is to assign a scale to each attribute. In this project, an automatic scale calculator called the data-collection template was used with the DEXi model. For qualitative attributes, the user chooses one of at least two options, each of which belongs to a scale. For each quantitative indicator, multiple thresholds are defined for each scale. The user provides the value of the indicator, and the associated option in the attribute's scale is automatically assigned according to the threshold values. Thus, DEXi evaluates a scenario by compiling "utility functions" and provides qualitative output (e.g., "the scenario is good"). It can also provide sub-assessments: "the scenario is good, but this branch is poor". Thus, by subdividing the overall assessment, it can identify the attributes to focus on to improve the overall result. Evaluating multiple scenarios with the same

DEXi model enables users to rank them according to the sub-problems and choose the best trade-off.

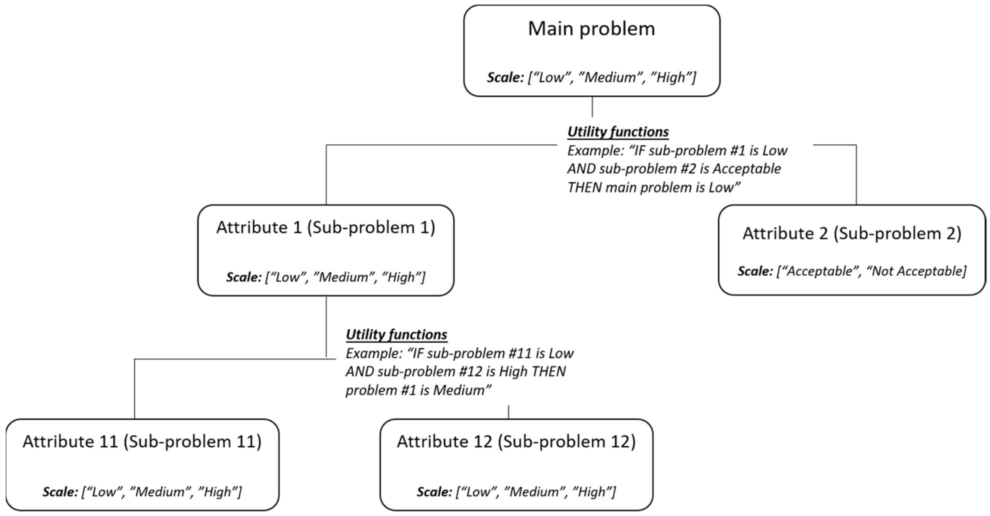


Figure 1. Description of the principles and lexical field of DEXi.

The development of DEXiAqua is detailed in the next section. First, the experts involved in the process are presented. Then, the first step is detailed, which consisted of creating the initial list of indicators from a literature review. Finally, the method used with experts and partners to build the model is described, as is the model itself. The data-collection template is then described. It is available upon request to the authors.

2.2. Development of DEXiAqua

2.2.1. Composition of the Working Groups

The partners of the SIMTAP project were involved in each step of building DEXiAqua: attribute selection, weighting, and threshold definition. To select the attributes, we formed multidisciplinary working groups:

- Economic: Théo Dubois (aquaculture, sustainability assessment using DEXi modeling), Nouraya Akkal-Corfini (vegetable production system design and multicriteria performance assessment of cropping systems using DEXi modeling), Alberto Barbaresi, Daniele Torreggiani and Enrica Santolini (design of smart agri-food structures and systems, energy modeling and renewable energy in agri-food and livestock systems, precision livestock farming, GIS spatial analysis and land suitability analysis, rural planning), Juan Francisco Fierro (aquaponics, aquaculture), Lorenzo Rossi (animal production, aquaculture, aquaponics), Romain Vandame (company director of Agriloops, which produces prawns and vegetables in aquaponics systems), Rainer Linke (legal counsel and head of government advisors);
- Social: Joël Aubin (environmental assessment (LCA) and agriculture system design), Jacopo Bacenetti (applying LCA to agricultural processes), Michele Costantini (applying the LCA to agricultural processes), Kyle Spiteri (diversification and scientific trials of agricultural production), Samuel Le Féon (environmental assessment using LCA), Chingoileima Maibam (marine biology and ecology, reproduction and nutrition of polychaetes);
- Environmental: Christophe Jaeger (environmental assessment and design of aquacultural systems), Aurélie Wilfart (environmental assessment of livestock systems using LCA and emergy accounting, nutrition and environmental optimization of livestock systems), Alberto Pardossi (irrigation and fertigation management of horticultural crops), Carlo Bibbiani (innovative rural building design, modeling energy and gas exchanges in greenhouse systems, aquaculture facilities), Baldassare Fronte (aquaculture, aquaponics, reproduction, and nutrition of marine fish species), Mehmet Ali

Koçer (environmental monitoring and management related to eutrophication and microalgae, environmental impacts and management of aquaculture), Hüseyin Sevgili (fish nutrition and aquaculture).

2.2.2. Toward a Library of Attributes: Literature Review and Relevant Assessment Methods

The first step in assessing the sustainability of aquaculture systems using DEXi consisted of defining the relevant sustainability issues and how to qualify them. It entailed observing how the literature evaluated the three branches of sustainability. Approximately 60 references from the literature and project reports were analyzed to build an initial list of 413 potential attributes and indicators for aquaculture systems.

This step identified several key assessment methods to use: life cycle assessment (LCA), emergy accounting (accounting of the solar energy consumed directly and indirectly by the system), life cycle costing (LCC), and social life cycle assessment (SLCA). LCA quantifies potential environmental impacts. As a life cycle-oriented method, it assesses impacts throughout the life cycle of the studied system. As a multicriteria method, it calculates multiple environmental impacts. The principles and guidelines of LCA are internationally standardized [43,44]. LCA is widely used to estimate the environmental impacts of aquaculture systems [11,45–47]. It has been applied recently to IMTA systems [48,49]. In the SIMTAP project, life cycle impact assessment will be performed for seven environmental impact categories considered essential to assess for aquaculture systems by the project partners:

- Eutrophication potential [50];
- Acidification potential [50];
- Global warming potential [50];
- Land competition [50];
- Cumulative energy demand [51];
- Available water remaining [52];
- Net primary production use [53].

Emergy accounting is a quantitative top-down approach that transforms each nonmonetary flow (e.g., sun, rain, wind) and monetary flow (e.g., products, services) into its equivalent solar energy content using a common unit, the solar emjoule [54]. It has been applied to aquaculture systems [55,56] in combination with LCA [57]. Two emergy indicators were included in DEXiAqua: emergy yield ratio and percentage of renewability, which reflect the system's ability to use local natural resources and renewable resources, respectively.

LCC assesses the economic sustainability of a process, product, or service over time, focusing primarily on its costs. Although LCC predates LCA, it is not standardized, and no official guidelines exist for implementing it. General codes of practice have been developed [58], but many conceptual frameworks have been adopted in the literature, the most common of which is the use of conventional LCC, based on private cash-flow models [59]. The latter approach was therefore selected to evaluate the economic performance of SIMTAP systems but also to compare them to commercial aquaculture facilities. In the SIMTAP project, this assessment refers not to the product sold at the farm gate (i.e., farmed fish and other potential co-products) but rather to an operational aquaculture plant and its life span. Therefore, all costs were considered when building the model, including the initial capital investment and future ordinary and extraordinary expenses for operation and maintenance; capital depreciation and costs of resale, recovery, or disposal; and the income derived from subsidies and the sale of products. Some of the indicators selected could be calculated directly from this model (i.e., net present value and internal rate of return). Some values from the cash-flow model were used as inputs for secondary calculations (e.g., the gross value added from plant operations was used to calculate the labor productivity indicator in the economic branch).

SLCA, also based on LCA principles, combines quantitative and qualitative data to identify, evaluate and manage social impacts [60]. Social impacts are consequences, either positive or negative and direct or indirect, related to the life cycle of a product or service that influence the stakeholders involved. SLCA guidelines were published by the UNEP/SETAC Life Cycle Initiative [61,62] to unify the methodological approach with the social dimension of sustainability (e.g., identifying the stakeholders and attributes to evaluate the indicators to use). The principles dictated by these guidelines were considered when selecting the social sustainability indicators, along with their connections within the social branch. Specifically, a Type I SLCA was performed [63], which is based on giving a scale score to the selected indicators using thresholds (i.e., performance reference points) and on their subsequent weighting, a method that fits well within DEXiAqua. However, the guidelines provide a generic framework that is difficult to apply to specific sectors such as agriculture, fisheries, and forestry. Therefore, the framework was modified to adapt it to the reference context based on the literature review, which highlighted the social attributes relevant to the specific sector. One objective of the SIMTAP project is to characterize the social risks and benefits for stakeholders associated with aquaculture activities; therefore, a "gate-to-gate" approach was used for the aquaculture plants. The relevant stakeholders for this assessment include workers, consumers, society, and local communities. Indicators related to animal welfare were also considered in the "meeting social expectations" branch related to society. Previous SLCA studies in the field of animal production highlighted that this social aspect of the sector must be considered and evaluated [64,65]. To our knowledge, this is the first time an SLCA framework has been applied to aquaculture.

2.2.3. Consultation Process and Building of the DEXi Tree

The partners of the SIMTAP project were involved in the consultation process and participated in the steps described below (Figure 2). The DEXi method was first presented to the project consortium, with the objective to evaluate the sustainability of systems according to the three traditional branches of sustainability: environmental, social, and economic. An initial version of the tree (i.e., the division of the three main branches into multiple sub-branches) was based on the literature and former research projects. In particular, experience from the MASC project [31] was used. This initial tree was submitted to partners via an online survey so they could (i) validate sustainability dimensions and proposed attributes, (ii) propose additional attributes, if necessary, and (iii) rank attributes by importance based on their own experience. For each attribute, partners were asked to choose among five options: "Not relevant", "Not so important", "Important", "Major issue", and "I don't understand the attribute". The survey results validated the three sustainability dimensions and indicated the need to consider the quality of products, which had not been initially included. Thus, the initial version of the attribute tree was built. A workshop was then organized to share and discuss the tree with the partners to reach a consensus on the attributes to retain, remove or modify. For each attribute, three questions were asked and resolved: (i) "Do we keep the attribute?", (ii) "Do we validate its hierarchical connections to other attributes?", and (iii) "Does it need a more understandable name?". In the second part of the workshop, partners were divided into three workgroups, each of which focused on one of the three dimensions. Based on the initial tree proposed, workgroups were asked to validate the relevance of the attributes, their hierarchy with each other, and the completeness of the tree. The workgroups were encouraged to add or remove attributes if inconsistencies appeared during these additional discussions. They then developed indicators that represented each sub-attribute. The indicators needed to (i) be associated with available data, (ii) define scales and thresholds, and (iii) be able to distinguish differences among systems/scenarios. In addition, three rules were followed: to have few indicators for each sub-attribute, sufficient comprehensiveness, and no redundancy in indicators of the sub-attributes. The proposals from each workgroup were compiled to obtain a definitive version of the attribute tree. Then, a second online survey was sent to partners that asked them to weigh the criteria for each level of the tree. Mean values were used when the weights of participants converged. When they diverged, they were discussed and validated in the last workshop. During this workshop, the thresholds within the scale allocated to each indicator were also defined. Finally, a complete tree was obtained, thus dividing overall sustainability into sub-attributes that continued until they reached measurable indicators. The scales of these indicators were automatically defined according to the thresholds previously determined and recorded in the DEXi software.

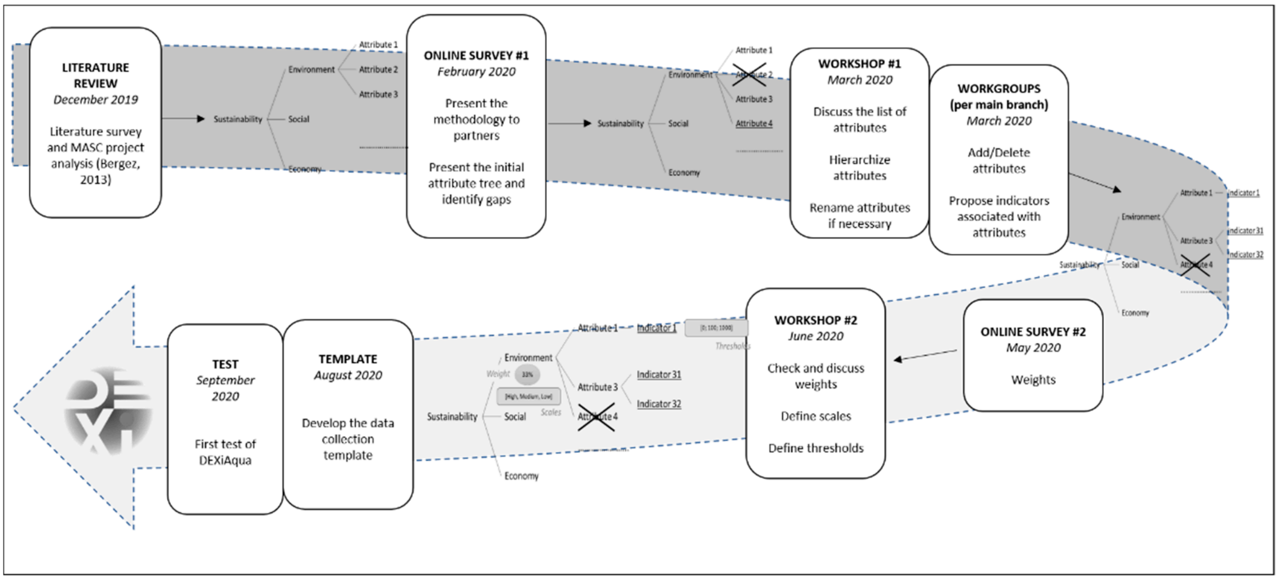


Figure 2. Steps involved in building DEXiAqua.

2.2.4. Data Collection and Attribute Calculation Template

To simplify collection of the many data sets needed to assess sustainability, a template was created with four objectives:

- Collect data for the DEXiAqua tree, including those needed for LCA, emergy analysis, LCC, and SLCA (Figure 3);
- Perform additional calculations to transform input data into DEXi attributes;
- Determine a scale for each DEXi attribute by combining the data set with defined thresholds;
- Generate the list of scales formatted for import into DEXi software and that correspond to the model developed.

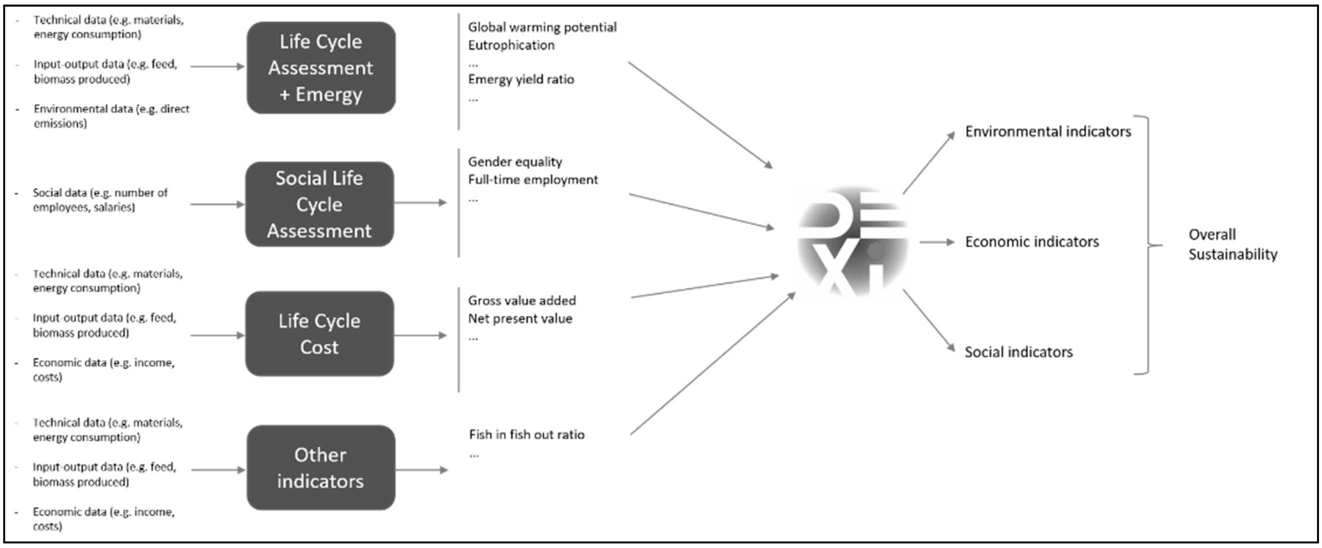


Figure 3. Overview of data collected in the data-collection template.

The template could not calculate all of the indicators itself. LCA and emergy indicators were calculated using other tools based on the data set collected, and then their results were incorporated into the template to determine the DEXi scales.

The template included the following:

- Sheets to fill out:
  - General system description;
  - Input data;
  - Calculation sheets: to help calculate input data;
  - LCA sheets: to collect data used to calculate LCA impact categories.
- Sheets to view and verify:
  - Instructions;
  - Secondary data calculation: calculate certain DEXi attributes from input data;
  - Indicators: compile DEXi attributes and determine scales;
  - DEXi export: format the scales into a list for import into the DEXi model for assessment.

One template must be filled for each system assessed in order to be able to compare sustainability among systems by exporting lists of scales into DEXi software. The template is available upon request.

2.3. Description of the Reference Case Study as a Synthetic Scenario

A reference case study was evaluated using DEXiAqua. This assessment involved applying the material developed to a data set, i.e., the comprehensiveness of the template and its ability to sort a formatted list of scales into input for the DEXi software. It assessed whether the DEXi model provides results that are understandable, consistent, and explainable based on the characteristics of a production system. The case study was based on a French fish farm that produced 56 tons of Atlantic salmon per year in a land-based recirculating aquaculture system. The water loop includes a mechanic filter extracting the suspended solids, stocked and sent for crop fertilization; a biologic filter for ammonia nitrification; and an ozonation device for disinfection and oxygenation of the water. The water is pumped from a brackish water table and released into the sea. The fish farm was chosen because it had been described in a previous study [57] and benefited from existing LCA and emergy accounting results. Since it had been previously studied in detail, we could analyze DEXiAqua results based on our knowledge and expectations. Additional data were extrapolated from the technical description of the site and the economic statistics of the sector. Thus, the case study did not completely refer to an existing farm but was a synthetic scenario based on estimates.

2.4. Initial Tests of the Sensitivity of DEXiAqua

To perform an initial sensitivity analysis, a Python script was used to generate randomized systems (Supplementary File S1). These random systems were assessed using DEXiAqua with DEXiEval, which consists of command lines written in the Windows Services console (available at: https://kt.ijs.si/MarkoBohanec/dexieval.html, accessed on 14 January 2020). Another Python script was used to export results to Microsoft® Excel (Supplementary File S1). Seven simulations were tested:

- "Random": a completely randomized simulation in which the value of the scale of each attribute was randomly generated;
- "Eco_Low", "Env_Low", and "Soc_Low", in which all attributes of the given dimension received the worst score, while the values of the remaining attributes were randomly generated;
- "Soc_Eco_Low", "Soc_Env_Low", and "Eco_Env_Low", in which all attributes of the two given dimensions received the worst score, while the values of the remaining attributes were randomly generated.

Results of the sensitivity analysis are shown in the Discussion section.

3. Results

3.1. Attribute Tree, Scales, and Thresholds

The method described was used to build an attribute tree divided into three main branches related to the three traditional dimensions of sustainability (i.e., environmental, social, and economic). Each branch was divided into several levels of attributes and sub-attributes to describe the complexity and unique characteristics of aquaculture systems. Indicators at the end of the branch expressed the corresponding attribute. For each attribute, a scale was defined to distinguish systems sufficiently without introducing too much complexity into the calculation method. For each quantitative attribute, thresholds were defined to help perform automatic scaling of values that were provided by users. Environmental, social and economic branches contained 27, 22, and 20 indicators, respectively (Tables 1–3, respectively) (see Table 4 for their definitions and Supplementary File S2 for detailed descriptions). Summary overviews of the three sustainability branches are available in Supplementary File S3.

3.2. Attribute Values and Scales of the Reference Case Study

Application of the DEXi method to the reference system yielded attribute values and associated scales (Table 5) (see Supplementary Files S4 and S5 for the template's data calculation sheet and indicator sheet that translated indicator values into scales, respectively). The values of some missing data were estimated to test the method since the case study had been studied in the past, and no more data about it could be obtained.

3.3. DEXi Assessment Results for the Reference Case Study

The overall sustainability of the reference case study was assessed as medium (see Supplementary File S6 for a summary for each branch). Branch summaries were obtained using the freeware IZI-EVAL, developed in the MASC project [30,31]. Environmental, social and economic sustainability were assessed as medium, low and high, respectively (Table 6).

Based on low LCA impact scores, the reference case study appeared to have low negative impacts on ecosystems (Figure S1 in Supplementary File S6), especially for global impacts. The other environmental sub-branches were assessed as medium. Overall, general environmental scores were good (e.g., LCA scores), but only one species was reared in the system (i.e., salmon). Thus, the system was not as good for indicators related to diversification, output management, and decreasing inputs. Its respect for natural resources was assessed as medium because it used feed with relatively high environmental impacts and had a low level of renewability. It also required a large quantity of energy per ton of fish produced. Ecological efficiency was assessed as medium because recycling was limited (low score for the use of co-products as inputs), the large quantity of energy required did not come from renewable sources, and resources did not come from local sources. Biodiversity was not managed well (medium) due to a lack of predator control—which can be improved—and mono-trophic rearing, which was inherent to the system.

The system was economically viable due to low dependence on subsidies and high economic performance (Figure S2 in Supplementary File S6), which were assessed over a projected time horizon of 30 years. However, it could have been more autonomous and less vulnerable by reducing its dependence on suppliers and fisheries (due to the large quantities of fishmeal and fish oil in the diet). Production efficiency was assessed as medium. Despite high production costs, the production had high sales prices. This result was expected since salmon farming is one of the most profitable forms of aquaculture production in Europe [66]. Inland farms usually require much higher investment costs than those offshore. In this system, they were counterbalanced by (i) containment of consumed feed due to an excellent feed conversion ratio and (ii) no treatments for sea lice and related product losses, which are two major costs of salmon farming [67].

Table 1. Detailed environmental branch of the attribute tree, with description of scales, attributes, thresholds, and units. The hierarchy of attributes is represented by tabs and end with attributes (in italics). When an attribute is defined by several sub-attributes or indicators, the weights are also given. Units of the threshold values are given in the indicator description in Table 4.

Attribute—Sub-Attribute—*Indicator*	**Weight**	**Scale**	**Thresholds [1]**	**Unit**
Environmental sustainability		[Very Low; Low; Medium; High; Very High]		
Reduce negative impacts on ecosystems	30%	[Very Low; Low; Medium; High; Very High]		
Negative local impacts on ecosystems	60%	[Very High; High; Medium; Low; Very Low]		
Chemical and contaminant emissions	30%	[High; Medium; Low]		
Health costs		[High; Medium; Low]	[]∞; 0.06[; [0.06; 0.04[; [0.04; 0]]	€/kg
Contribution to local eutrophication	45%	[High; Medium; Low]		
Total nitrogen emissions	70%	[High; Medium; Low]	[]∞; 94[; [94; 40[; [40; 0]]	kg/ton
Suspended solid emissions	30%	[High; Medium; Low]	[]∞; 405[; [405; 57[; [57; 0]]	kg/ton
Local land competition	25%	[High; Medium; Low]		
On-farm land area used		[High; Medium; Low]	[]∞; 4[; [4; 0.2[; [0.2; 0]]	m^2/ton
Negative global impacts on ecosystems	40%	[Very High; High; Medium; Low; Very Low]		
Contribution to climate change	40%	[Very High; High; Medium; Low; Very Low]		
Global warming potential		[Very High; High; Medium; Low; Very Low]	[]∞; 8[; [8; 6[; [6; 4.5[; [4.5; 2[; [2; 0]]	ton CO_2 equivalent/ton
Contribution to acidification	25%	[High; Medium; Low]		
Acidification potential		[High; Medium; Low]	[]∞; 35[; [35; 15[; [15; 0]]	kg SO_2 equivalent/ton
Contribution to eutrophication	35%	[High; Medium; Low]		
Eutrophication potential		[High; Medium; Low]	[]∞; 70[; [70; 35[; [35; 0]]	kg PO_4^{3-} equivalent/ton
Respect availability of natural resources	30%	[Very Low; Low; Medium; High; Very High]		
Use sustainable resources	50%	[Very Low; Low; Medium; High; Very High]		
Use sustainable feed	45%	[Very Low; Low; Medium; High; Very High]		
Fish In:Fish Out ratio		[Very High; High; Medium; Low; Very Low]	[]∞; 6[; [6; 4.5[; [4.5; 3[; [3; 1.5[; [1.5; 0]]	#
Sustainable supply of juveniles and seeds	25%	[Low; Medium; High]		
Percentage of wild juveniles and seeds used		[High; Medium; Low]	[]∞; 50[; [50; 10[; [10; 0]]	%
Level of renewability of the activity	30%	[Low; Medium; High]		

Table 1. *Cont.*

Attribute—Sub-Attribute—*Indicator*	Weight	Scale	Thresholds [1]	Unit
Percentage of renewability		[Low; Medium; High]	[]∞; 40[; [40; 20[; [20; 0]]	%
Limit the use of resources	50%	[Very Low; Low; Medium; High; Very High]		
Pressure on water	30%	[High; Medium; Low]		
Water demand		[High; Medium; Low; Very Low]	[]∞; 125[; [125; 10[; [10; 1[; [1; 0]]	m^3/kg
Pressure on primary production	20%	[High; Medium; Low]		
Net primary production use		[High; Medium; Low]	[]∞; 85[; [85; 15[; [15; 0]]	kg C equivalent/kg
Pressure on land area	20%	[Very High; High; Medium; Low; Very Low]		
Global land competition		[Very High; High; Medium; Low; Very Low]	[]∞; 5500[; [5500; 2500[; [2500; 1500[; [1500; 800[; [800; 0]]	m^2/ton
Energy requirements	30%	[Very High; High; Medium; Low; Very Low]		
Total cumulative energy demand		[Very High; High; Medium; Low; Very Low]	[]∞; 110[; [110; 70[; [70; 45[; [45; 30[; [30; 0]]	GJ/ton
Increase ecological efficiency	30%	[Very Low; Low; Medium; High; Very High]		
Limit waste production and increase recycling	30%	[Very Low; Low; Medium; High; Very High]		
Use co-products as inputs	40%	[Low; Medium; High]		
Percentage of nitrogen derived from co-products		[Low; Medium; High]	[]∞; 50[; [50; 20[; [20; 0]]	%
Waste recycling	40%	[Low; Medium; High]		
Percentage of phosphorus recovered		[Low; Medium; High]	[]∞; 30[; [30; 10[; [10; 0]]	%
Limit organic waste production	20%	[Very Low; Low; Medium; High; Very High]		
Production loss		[Very High; High; Medium; Low; Very Low]	[]∞; 40[; [40; 30[; [30; 20[; [20; 10[; [10; 0]]	%
Farm input efficiency	50%	[Very Low; Low; Medium; High; Very High]		
Productivity of energy used	50%	[Very Low; Low; Medium; High; Very High]		
On-farm energy efficiency	50%	[Very Low; Low; Medium; High; Very High]	[[0; 0.5[; [0.5; 1[; [1; 1.5[; [1.5; 5[; [5; ∞]]	MWh/ton
Percentage of renewable energy used	50%	[Low; Medium; High]		
Feed efficiency	50%	[Very Low; Low; Medium; High; Very High]		
Total feed conversion rate	70%	[Very High; High; Medium; Low; Very Low]	[]∞; 2.2[; [2.2; 1.8[; [1.8; 1.6[; [1.6; 1.3[; [1.3; 0]]	kg/kg
Nitrogen-use efficiency	30%	[Low; Medium; High]	[]∞; 30[; [30; 15[; [15; 0]]	%

Table 1. *Cont.*

Attribute—Sub-Attribute—*Indicator*	Weight	Scale	Thresholds [1]	Unit
Use local resources	20%	[Very Low; Low; Medium; High; Very High]		
Feedstuff locally produced	50%	[Low; Medium; High]	[]∞; 60[; [60; 40[; [40; 0]]	%
Emergy yield ratio	50%	[Low; Medium; High]	[]∞; 2[; [2; 1.1[; [1.1; 0]]	#
Enhance biodiversity	10%	[Very Low; Low; Medium; High; Very High]		
Protection of local fauna and flora species	35%	[Very Low; Low; Medium; High]		
Predator control	40%	[Not Acceptable; Acceptable]	[Option 1; Option 2] [2]	#
Disease management	60%	[Low; Medium; High]		
Biosecurity and good practices		[Low; Medium; High]	[]∞; 4[; [4; 2[; [2; 0]]	#
Foster polyculture and integrate natural cycles	35%	[Very Low; Low; Medium; High]		
Multitrophic integration	50%	[Low; Medium; High]	[]∞; 3[; [3; 2[; [2; 0]]	#
Production diversification	50%	[Low; Medium; High]	[]∞; 5[; [5; 2[; [2; 0]]	#
Maintenance of genetic diversity	30%	[Low; Medium; High]		
Escapee management		[High; Medium; Low]	[]∞; 4[; [4; 0.5[; [0.5; 0]]	%Ù

[1] Each interval corresponds to the scale in the previous column. [2] Refer to Supplementary File S2.

Table 2. Detailed social branch of the attribute tree, with description of scales, attributes, thresholds, and units. The hierarchy of attributes is represented by tabs and end with attributes (in italics). When an attribute is defined by several sub-attributes or indicators, the weights are also given. Units of the threshold values are given in the indicator description in Table 4.

Attribute—Sub-Attribute—*Indicator*	**Weight**	**Scale**	**Thresholds** [1]	**Unit**
Social sustainability		[Very Low; Low; Medium; High; Very High]		
Relationship with other stakeholders	15%	[Very Low; Low; Medium; High; Very High]		
Quality of the relationship with professional institutions	50%	[Low; Medium; High]		
Interactions with professional institutions	60%	[Low; Medium; High]	[Option 1; Option 2; Option 3] [2]	#
Professional involvement	40%	[Low; Medium; High]	[]∞; 5[; [5; 1[; [1; 0]]	#
Quality of the relationship with customers and suppliers [3]	50%	[Low; Medium; High]		
Independence from suppliers	100%	[Low; Medium; High]	[]∞; 50[; [50; 30[; [30; 0]]	%
Independence from customers	0%	[Low; Medium; High]	[]∞; 50[; [50; 25[; [25; 0]]	%
Employment and working conditions	30%	[Very Low; Low; Medium; High; Very High]		
Guarantee of staff protection and fulfillment	50%	[Very Low; Low; Medium; High; Very High]		
Workload	25%	[High; Medium; Low]	[]∞; 2200[; [2200; 1600[; [1600; 0]]	h/FTE/year
Health and safety	30%	[Low; Medium; High]	[]∞; 2[; [2; 1[; [1; 0]]	Number of days lost/1000 h
Assessment of job difficulty	15%	[High; Medium; Low]	[Option 1; Option 2; Option 3]	#
Labor remuneration	30%	[Low; Medium; High]	[]∞; 1.5[; [1.5; 1[; [1; 0]]	#
Conditions of employment	50%	[Very Low; Low; Medium; High; Very High]		
Working status	25%	[Low; Medium; High]	[]∞; 80[; [80; 60[; [60; 0]]	%
Education level	35%	[Low; Medium; High]	[]∞; 30[; [30; 10[; [10; 0]]	%
Equal opportunities	40%	[Very Low; Low; Medium; High; Very High]		
Gender equality	70%	[Low; Medium; High]	[Option 1; Option 2; Option 3] [2]	#
Employment of workers with disabilities	30%	[No; Yes]	[No; Yes]	#
Meeting societal expectations	25%	[Very Low; Low; Medium; High; Very High]		
Respect of animal welfare	30%	[Very Low; Low; Medium; High; Very High]		
Production health management	50%	[Very Low; Low; Medium; High; Very High]		

Table 2. *Cont.*

Attribute—Sub-Attribute—*Indicator*	Weight	Scale	Thresholds [1]	Unit
Production loss	70%	[Very High; High; Medium; Low; Very Low]	[]∞; 40[; [40; 30[; [30; 20[; [20; 10[; [10; 0]]	%
Fish physical damage	30%	[High; Medium; Low]	[]∞; 20[; [20; 4[; [4; 0]]	%
Rearing environment	50%	[Very Low; Low; Medium; High; Very High]		
Stocking density	60%	[High; Medium; Low]	[]∞; 45[; [45; 22[; [22; 0]]	kg/m^3
Biosecurity and good practices	40%	[Low; Medium; High]	[]∞; 4[; [4; 2[; [2; 0]]	#
Contribution to food security	35%	[Very Low; Low; Medium; High; Very High]		
Assured supply of food products	50%	[Very Low; Low; Medium; High; Very High]	[]∞; 17.5[; [17.5; 12.5[; [12.5; 7.5[; [7.5; 2.5[; [2.5; 0]]	ton of dry matter/FTE
Accessibility of products	50%	[Very Low; Low; Medium; High; Very High]	[[0; 4[; [4; 4.5[; [4.5; 5.5[; [5.5; 6.5[; [6.5; ∞]]	#
Production of quality-based products	35%	[Very Low; Low; Medium; High; Very High]		
Level of product quality		[Very Low; Low; Medium; High; Very High]		
Nutritional quality	40%	[Very Low; Low; Medium; High; Very High]	[]∞; 25[; [25; 20[; [20; 15[; [15; 10[; [10; 0]]	g [EPA + DHA]/100 g
Fish physical damage	60%	[High; Medium; Low]	[]∞; 20[; [20; 4[; [4; 0]]	%
Contribution to local development	30%	[Very Low; Low; Medium; High; Very High]		
Contribution to employment	45%	[Very Low; Low; Medium; High; Very High]		
Local supply	35%	[Low; Medium; High]		
Feedstuff locally produced		[Low; Medium; High]	[]∞; 60[; [60; 40[; [40; 0]]	%
Multifunctionality	20%	[Low; Medium; High]		
Education contribution		[Low; Medium; High]	[Option 1; Option 2; Option 3]	#

[1] Each interval corresponds to the scale in the previous column. [2] Refer to Supplementary File S2. [3] The experts in the project considered only independence from suppliers due to the prospective state of the IMTA systems developed. However, independence from a single customer was mentioned as an important criterion for future operational systems and was retained in the tree to include later.

Table 3. Detailed economic branch of the attribute tree, with description of scales, attributes, thresholds, and units. The hierarchy of attributes is represented by tabs and end with attributes (in italics). When an attribute is defined by several sub-attributes or indicators, the weights are also given. Units of the threshold values are given in the indicator description in Table 4.

Attribute—Sub-Attribute—*Indicator*	Weight	Scale	Thresholds [1]	Unit
Economic sustainability		[Very Low; Low; Medium; High; Very High]		
Production efficiency	40%	[Very Low; Low; Medium; High; Very High]		
Productivity	45%	[Very Low; Low; Medium; High; Very High]		
Resource productivity	60%	[Very Low; Low; Medium; High; Very High]		
On-farm energy efficiency	40%	[Very Low; Low; Medium; High; Very High]	[[0; 0.5[; [0.5; 1[; [1; 1.5[; [1.5; 5[; [5; ∞]]	MWh/ton
Labor productivity	30%	[Very Low; Low; Medium; High; Very High]	[]∞; 2[; [2; 1.5[; [1.5; 1.25[; [1.25; 1[; [1; 0]]	#
Total feed conversion rate	30%	[Very High; High; Medium; Low; Very Low]	[]∞; 2.2[; [2.2; 1.8[; [1.8; 1.6[; [1.6; 1.3[; [1.3; 0]]	kg/kg
Production management	40%	[Very Low; Low; Medium; High; Very High]		
Production loss	40%	[Very Low; Low; Medium; High; Very High]		
Level of product quality	60%	[Very Low; Low; Medium; High; Very High]		
Nutritional quality	40%	[Very Low; Low; Medium; High; Very High]	[]∞; 25[; [25; 20[; [20; 15[; [15; 10[; [10; 0]]	g [EPA + DHA]/100 g
Fish physical damage	60%	[High; Medium; Low]	[]∞; 20[; [20; 4[; [4; 0]]	%
Sales price sufficient given production costs	55%	[Very Low; Low; Medium; High; Very High]		
Production value	50%	[Very Low; Low; Medium; High; Very High]		
Average sales price		[Very Low; Low; Medium; High; Very High]	[]∞; 6.5[; [6.5; 5.5[; [5.5; 4.5[; [4.5; 4[; [4; 0]]	€/kg
Production cost	50%	[Very High; High; Medium; Low; Very Low]		
Paid labor costs	30%	[Very High; High; Medium; Low; Very Low]	[]∞; 1[; [1; 0.8[; [0.8; 0.6[; [0.6; 0.4[; [0.4; 0]]	€/kg
Feed costs	50%	[Very High; High; Medium; Low; Very Low]	[]∞; 2[; [2; 1.7[; [1.7; 1.5[; [1.5; 1.3[; [1.3; 0]]	€/kg
Juvenile and seedling costs	20%	[Very High; High; Medium; Low; Very Low]	[]∞; 1.1[; [1.1; 0.9[; [0.9; 0.7[; [0.7; 0.5[; [0.5; 0]]	€/kg
Viability	60%	[Very Low; Low; Medium; High; Very High]		
Profitability	50%	[Low; Medium; High]		
Net present value	50%	[Low; Medium; High]	[>0; = 0; < 0]	€
Internal rate of return	50%	[Low; Medium; High]	[>6%; = 6%; < 6%]	%

Table 3. *Cont.*

Attribute—Sub-Attribute—*Indicator*	Weight	Scale	Thresholds [1]	Unit
Level of autonomy	20%	[Very Low; Low; Medium; High]		
Subsidy dependence	40%	[High; Medium; Low]		
Subsidies weight		[High; Medium; Low]	[]∞; 0.42[; [0.42; 0.22[; [0.22; 0]]	€/kg
Resource dependence	40%	[High; Medium; Low]		
Emergy yield ratio		[Low; Medium; High]		
Vulnerability	30%	[Very High; High; Medium; Low; Very Low]		
Level of sensitivity to pathological risks	25%	[Very High; High; Medium; Low]		
Production diversification	40%	[Low; Medium; High]	[]∞; 5[; [5; 2[; [2; 0]]	#
Biosecurity and good practices	60%	[Low; Medium; High]	[]∞; 4[; [4; 2[; [2; 0]]	#
Resistance to environmental constraints	35%	[Very Low; Low; Medium; High; Very High]	[[0; 6[; [6; 12[; [12; 18[; [18; 24[; [24; ∞]]	#
Resistance to commercial risks	40%	[Low; Medium; High; Very High]		
Specialization rate	33%	[High; Medium; Low]	[]∞; 80[; [80; 50[; [50; 0]]	%
Independence from suppliers	33%	[Low; Medium; High]	[]∞; 50[; [50; 30[; [30; 0]]	%
Independence from customers [2]	0%	[Low; Medium; High]	[]∞; 50[; [50; 25[; [25; 0]]	%
Dependence on fisheries	33%	[Very High; High; Medium; Low; Very Low]		
Fish In:Fish Out ratio		[Very High; High; Medium; Low; Very Low]	[]∞; 6[; [6; 4.5[; [4.5; 3[; [3; 1.5[; [1.5; 0]]	#

[1] Each interval corresponds to the scale in the previous column. [2] The experts in the project considered only independence from suppliers due to the prospective state of the IMTA systems developed. However, independence from a single customer was mentioned as an important criterion for future operational systems and was retained in the tree to include later.

Table 4. Description of indicators used in DEXiAqua.

Indicator	Unit	Description
On-farm energy efficiency	MWh/ton	Quantity of energy used per ton of biomass produced
Total feed conversion rate	kg/kg	Quantity of feed used per kg of biomass produced
Labor productivity	#	Gross value added divided by total labor costs
Production loss	%	Percentage of biomass produced that is lost
Nutritional quality	g [EPA + DHA]/100 g	Quantity of omega-3 fatty acids per 100 g of biomass
Average sales price	€/kg	Gross sales per kg of biomass produced
Paid labor costs	€/kg	Labor costs per kg of biomass produced
Feed costs	€/kg	Feed costs per kg of biomass produced
Juvenile and seedling costs	€/kg	Juvenile and seedling costs per kg of biomass produced
Net present value	€	Sum of expected future cash flows discounted at the appropriate discount rate
Internal rate of return	%	Discount rate at which discounted benefits equal discounted costs
Subsidies weight	€/kg	Subsidies received per kg of biomass produced
Emergy yield ratio	#	Ability of the system to use local resources according to emergy accounting
Production diversification	#	Number of planned species reared in the system
Biosecurity and good practices	#	Score from 0–5 based on existing disinfection measures
Resistance to environmental constraints	#	Score from 0–36 based on the probability and severity of four environmental constraints
Specialization rate	%	Percentage of total income from the main product
Independence from suppliers	%	Percentage of total inputs that are self-produced
Independence from customers	%	Percentage of total income derived from the largest customer
Fish in:fish out ratio	#	Dependence of the system on wild fish resources
Interactions with professional institutions	#	Choice among options that considers the number of interactions and representatives
Professional involvement	#	Number of seminars or professional meetings attended per year
Workload	h/FTE/year	Number of hours worked per year per full-time equivalent (FTE)
Health and safety	days lost/1000 h	Number of sick-leave days per 1000 h worked
Assessment of job difficulty	#	Choice among options that considers job complexity and stressfulness

Table 4. *Cont.*

Indicator	Unit	Description
Labor remuneration	#	Average salary divided by the minimum wage of the country
Working status	%	Percentage of permanent contracts
Education level	%	Percentage of professionally trained employees
Gender equality	#	Percentage of employees who are women, and consideration of their relative pay
Employment of workers with disabilities	#	"Yes" if at least one worker with a disability in the past 5 years
Fish physical damage	%	Percentage of fish with skin or fin damage
Stocking density	kg/m^3	Average mass of biomass reared per m^3
Assured supply of food products	ton DM/FTE	Dry matter biomass produced per full-time equivalent
Accessibility of products	#	Average sales price compared to the monthly minimum wage of the country
Contribution to employment	FTE/100 000 €	Number of full-time equivalents per 100 000 euros of income
Feedstuff locally produced	%	Percentage of feedstuff produced in the country
Education contribution	#	Choice among options that considers the number of trainees, educational tours and presentations to students
Health costs	€/kg	Costs of chemicals per kg of biomass produced
Total nitrogen emissions	kg/ton	Quantity of nitrogen released per ton of biomass produced
Suspended solid emissions	kg/ton	Quantity of suspended solids released per ton of biomass produced
On-farm land area used	m^2/ton	Area necessary per ton of biomass produced
Global warming potential	ton CO_2 equivalent/ton	Quantity of greenhouse gases emitted by the system
Acidification potential	kg SO_2 equivalent/ton	Contribution of the system to acidification of the surrounding environment
Eutrophication potential	kg PO_4^{3-} equivalent/ton	Contribution of the system to eutrophication
Percentage of renewability	%	Ability of the system to use sustainable resources according to emergy accounting
Percentage of wild juveniles and seeds used	%	Percentage of juveniles and of wild fish and seeds of wild plants used
Water demand	m^3/kg	System pressure on water resources
Net primary production use	kg C equivalent/kg	System pressure on biotic resources
Global land competition	m^2/ton	System pressure on land occupation
Total cumulative energy demand	GJ/ton	Quantity of direct and indirect energy used by the system

Table 4. *Cont.*

Indicator	Unit	Description
Percentage of nitrogen derived from co-products	%	Percentage of feed and fertilizer from co-products and by-products
Percentage of phosphorus recovered	%	Percentage of phosphorus recycled by other organisms inside the system
Percentage of renewable energy used	%	Percentage of energy from renewable sources
Nitrogen-use efficiency	%	Percentage of nitrogen input recovered in output biomass
Predator control	#	Use, or not, of lethal predator control (not acceptable/acceptable)
Multitrophic integration	#	Number of trophic levels of planned reared species
Escapee management	%	Percentage of escapees

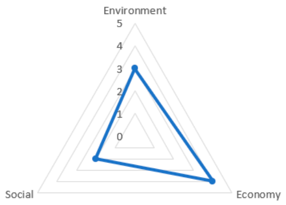
Table 5. Attribute values of the reference case study.

Attribute	Unit	Value	Scale
On-farm energy efficiency	MWh/ton	5.33	Very Low
Total feed conversion rate	kg/kg	1.02	Very Low
Labor productivity	#	3.3	Very High
Production loss	%	0.8%	Very Low
Nutritional quality	g [EPA + DHA]/100 g	20	High
Average sales price	€/kg	10	Very High
Paid labor costs	€/kg	1.1	Very High
Feed costs	€/kg	1.8	High
Juvenile and seedling costs	€/kg	0.1	Very Low
Net present value	€	4,546,362	High
Internal rate of return	%	87%	High
Subsidies weight	€/kg	0	Low
Emergy yield ratio	#	1.07	Low
Production diversification	#	1	Low
Biosecurity and good practices	#	4	High
Resistance to environmental constraints	#	11	High
Specialization rate	%	100%	High
Independence from suppliers	%	0	Low
Independence from customers	%	17.86%	High
Fish in:fish out ratio	#	5.7	High
Interactions with professional institutions	#	Option 1	Low
Professional involvement	#	3	Medium
Workload	h/FTE/year	2000	Medium
Health and safety	days lost/1000 h	0.75	Low
Assessment of job difficulty	#	Option 2	Medium
Labor remuneration	#	1.64	High
Working status	%	100%	High
Education level	%	100%	High
Gender equality	#	Option 3	Low
Employment of workers with disabilities	#	Yes	Yes
Fish physical damage	%	10%	Medium
Stocking density	kg/m^3	20	Low
Assured supply of food products	ton DM/FTE	7.8	Medium
Accessibility of products	#	6.57	Very Low
Contribution to employment	FTE/100 000 €	0.36	Very Low
Feedstuff locally produced	%	0%	Low
Education contribution	#	Option 2	Medium
Health costs	€/kg	0.18	High
Total nitrogen emissions	kg/ton	22.7	Low

Table 5. *Cont.*

Attribute	Unit	Value	Scale
Suspended solid emissions	kg/ton	57.7	Medium
On-farm land area used	m^2/ton	272.3	High
Global warming potential	ton CO_2 equivalent/ton	3.14	Low
Acidification potential	kg SO_2 equivalent/ton	12.8	Low
Eutrophication potential	kg ${PO_4}^{3-}$ equivalent/ton	34.3	Low
Percentage of renewability	%	10.66%	Low
Percentage of wild juveniles and seeds used	%	0%	Low
Water demand	m^3/kg	124	Medium
Net primary production use	kg C equivalent/kg	32	Medium
Global land competition	m^2/ton	1000	Low
Total cumulative energy demand	GJ/ton	105.8	High
Percentage of nitrogen derived from co-products	%	0%	Low
Percentage of phosphorus recovered	%	18%	Medium
Percentage of renewable energy used	%	0%	Low
Nitrogen-use efficiency	%	58.4%	High
Predator control	#	Option 1	Not acceptable
Multitrophic integration	#	1	Low
Escapee management	%	0%	Low

Table 6. Sustainability scores for each sustainability branch and its first-level sub-branches for the reference case study.

Overall Sustainability Graph	Branch	Score	Sub-Branch	Score
	Environment	Medium	Reduce negative impacts on ecosystems	High
			Respect availability of natural resources	Medium
			Increase the ecological efficiency of the activity	Medium
			Enhance biodiversity	Medium
	Economy	High	Production efficiency	Medium
			Viability	High
	Social	Low	Relationship with other stakeholders	Very low
			Employment and working conditions	Medium
			Meeting social expectations	Medium
			Contribution to local development	Very low

The system's social sustainability was assessed as low (Figure S3 in Supplementary File S6) due mainly to relationships with other stakeholders. In particular, the system depended greatly on suppliers and did not develop relationships with professional institutions. This low score was thus due to the small contribution to local development. The system created few jobs and imported many of its inputs, especially feedstuffs. The salmon produced was less accessible to consumers due to its high price, and the system did not meet social expectations completely. Employment and working conditions suffered from gender inequality (no women were employed) and the low level of health and safety conditions (due to a large number of sick-leave days).

4. Discussion

4.1. Developing a General Method to Assess the Sustainability of Aquaculture Systems

Several difficulties were addressed while developing the method that should be considered when using DEXiAqua. First, the model was developed with partners in a single project and with the objective to assess aquaculture systems. The partners are experts in aquaculture systems and were asked to think in general terms, but they necessarily based their input on their personal experience and the multitrophic context of the SIMTAP project. DEXIAqua could thus lack some information needed to assess the sustainability of specific systems. From the SIMTAP project perspective, the attributes considered are the most relevant and allows to assess the sustainability of aquaculture systems. However, divergences existed between experts during the workshops and should exist with the community. For example, recent discussions appeared about the consideration of food safety and its introduction in the model should be discussed in the future. Consequently, DEXiAqua is an iterative model that should be improved in the future, if needed. Uses and feedbacks will be helpful.

When evaluating economic profitability, the results reflect uncertainty in the projected economic performance of the production system throughout its life span. For the reference case study, costs of raw materials and labor, as well as fish production and sales prices, were assumed not to change over time. Nonetheless, price volatility, especially for the fish-derived ingredients consumed [67], could influence production costs strongly, and changes in regulations or consumer behavior could alter product supply and demand and influence the sales price. DEXiAqua reflects these considerations by assessing the system's vulnerability and degree of autonomy in the economic branch. In addition, the template developed can be used easily to modify the production and cost parameters in sensitivity analyses to verify their influence. Finally, for convenience, the economic assessment was based on private risks, costs, and income. According to an alternative approach called societal LCC, externalities should also be monetized and internalized, and this approach could be integrated into DEXiAqua in the future.

Defining the scaled attributes and the associated indicators and thresholds is an important added value of the model. When assessing sustainability, multiple systems are usually compared. Because this is a general feature of MCDA, it is recommended to define well the goal and scope of the assessment, initial questions, and reasons for the assessment. Rather than determining whether a future system has a high score, it is more important to know whether that system is better than existing systems. Defining a general conceptual framework with general values to compare is a step toward evaluating the sustainability of a system intrinsically. Thus, considering attributes related to multitrophic systems should lower the scores of mono-trophic systems, all other things being equal.

The case study increases our confidence in the model and its ability to evaluate the overall sustainability of aquaculture systems. Systems have many attributes, which reflects their complexity, but DEXiAqua can simplify them into sub-problems that are easier to assess and for which data are collectible. This responds to the objectives perfectly. The model can rebuild the cause-effect chain to explain the scores obtained for each sustainability branch related to expert knowledge about the system's specific characteristics. This can identify hotspots and potentially identify recommendations.

4.2. Questions about Increasing the Complexity and Diversity of the Systems and Assessing IMTA Systems from Prototype Data

The project includes partners from several countries. The steps used to build the model revealed predictable differences between partners. During workshops and online surveys, participants answered questions based on their perceptions, knowledge background, and geographic context. This context implies a variety of social, economic, environmental, and regulation situations. Accordingly, some indicators were more important for certain participants. Some indicators differ more among systems, and for others, data availability may differ among contexts and case studies. For example, legislation on and perception of working conditions can differ among countries. The partners reached a consensus on some indicators by reflecting national averages. For example, income is not assessed in absolute value but rather in relation to a national average. The ability to adapt indicators, thresholds, scales, and weights was maintained. However, comparing systems from differing contexts requires using common values. Besides spatial differences in social, economic, and possibly environmental contexts, temporal changes must be considered. The current values in DEXiAqua resulted from a consensus among experts at a specific time—around 2020. They may need to change over time to reflect the reality of future systems better. This ability to evolve is a key point as it refers to the possible lack of consideration of the concerns and challenges of users cited as the most common reason for the lack of involvement in the use of assessment models [68].

Another important point is the diversity of systems. Besides differing geographically and temporally, IMTA systems also differ technically. For example, some are set in the nearshore directly using marine water, while others are set in buildings using reconstituted saltwater. Systems contain different species of different sizes. This variability suggests that, for certain systems, the current list of indicators lacks necessary indicators or, conversely, contains irrelevant indicators. Indicators should be added by keeping in mind the difficulty to reach both exhaustivity and simplicity [32]. Again, the data-collection and indicator-calculation template can be adapted to prevent this lack. If necessary, users should modify the template to assess their system better, but systems must still be compared using the same model. The assessment level could also be an important point to discuss depending on the systems. In our study, the reuse of material and energy is mainly considered at the farm level, where the management decisions of the farmer are applied. We considered the origin of the inputs and their potential recycled sources. Nevertheless, the fate of co-products downstream the farm, and their potential recycling by other actors in the territories, are poorly included. This is a way of improvement in future versions of the assessment method.

DEXiAqua was tested on a monoculture system that had been studied in previous projects. Thus, an important parameter was not considered: the time needed to collect data. Data collection was difficult, even for a simple system, due to the large number of indicators required to reflect overall sustainability. Data collection will likely be more complicated and time-consuming for new systems, especially multitrophic systems. This pitfall was partly expected because the model was designed according to project partners who knew well what kind of data should be collected. It was also expected due to the data-collection template's inclusion of calculation sheets to simplify collection. However, the attributes used depend on other methods whose results cannot be calculated automatically. For example, the template helps collect data to calculate LCA indicators, but it cannot actually calculate them. Doing so requires the intervention of an expert.

One remaining factor was not expected and will be a future focus of the project. The SIMTAP project will design and construct prototypes from which data can be collected. These are not operational systems. Comparing IMTA systems to traditional systems requires upscaling the former to convert prototype data into a potential operational system. Some of the data for future operational systems will need to be estimated since they will not be available for a prototype (e.g., quantity of subsidies, sales price).

4.3. Initial Results and Discussion of the Sensitivity of the Model

In the sensitivity simulations, the results of each scenario had a Gaussian distribution (Figure 4). Results of the random scenario ranged mostly from "medium to low" to "medium to high" scores and almost never received extreme scores. Thus, it was difficult to obtain systems with extremely high or low scores. This result may lead us to reconsider final scale names in future versions of the model (e.g., changing "medium to low" to "low") to communicate about overall sustainability better. The lack of spread in overall scores could also challenge the model's ability to distinguish systems well. Indeed, the model quite poorly discriminates aquaculture systems. This was also one of the conclusions of sensitivity analysis made on the MASC model [69]. Another reason for the lack of discrimination can be linked to the compensation and/or correlation between indicators [31,32]. This will be a focus once more results from real systems have been obtained.

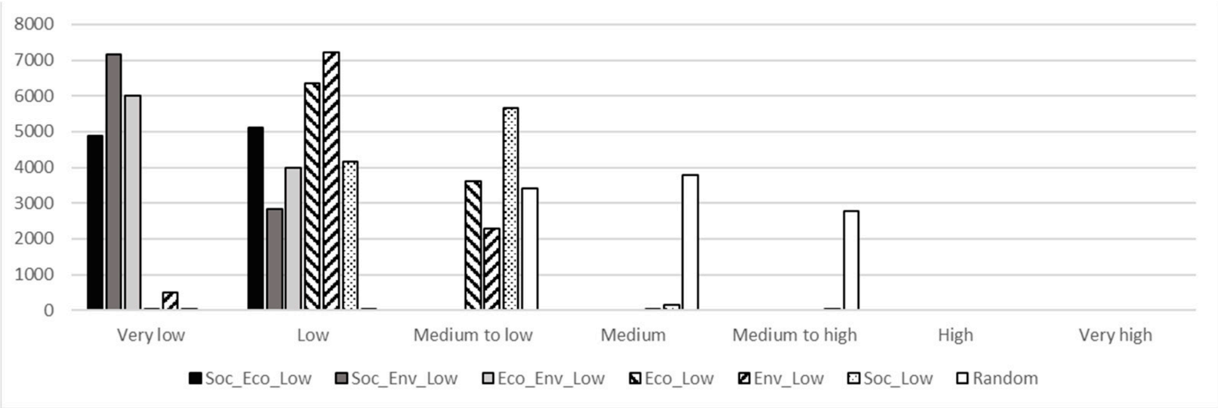


Figure 4. Distributions of overall sustainability scores of 10,000 randomized simulations of DEXiAqua for seven scenarios: 3 x_y_Low, in which all indicators of two sustainability branches x and y (i.e., Soc(ial), Eco(nomic), and Env(ironmental)) were set to their lowest value and the others were randomized; 3 x_Low, in which all indicators of one sustainability branch x were set to their lowest value and the others were randomized; and Random, in which the values of all indicators were randomized.

By setting attributes to extreme values, the distribution of overall scores moved toward lower scores, meaning that systems with low scores theoretically exist. When one dimension had a low score, the overall sustainability was usually "low" and "medium to low". When two dimensions had low scores, the overall sustainability was usually "very low" and "low". Interestingly, dimensions differed in their influence on overall sustainability, even though each dimension's branch contributes 33% of the overall score. This is because certain indicators are used in several branches of the attribute tree, meaning that they are related to several dimensions. For example, "production loss" is used to qualify animal welfare (part of social sustainability) and production management (part of economic sustainability). Since these scenarios were built by setting all indicators of one branch to a specific value, this can influence the other branches to greater or lesser degrees. Because environmental indicators are those most used in other branches, giving the environmental dimension a low score decreased the overall sustainability more than doing so with the economic or social dimensions. Consequently, even though each sustainability branch has the same weight, the branches are not completely balanced due to interconnected parameters, as also pointed out for the MASC model [69]. A system that has low environmental sustainability is more likely to have lower overall sustainability than a system that has low social sustainability. This should be a focus when assessing multiple real systems.

5. Conclusions

5.1. Theoretical Implications

This article describes a robust method to assess the sustainability of aquaculture systems with special emphasis on IMTA systems. It is based on combining parameters, including LCA, LCC, SLCA, and emergy accounting results, using DEXi freeware. A template was designed to help users easily provide data to perform the assessment. The template automatically transforms data into scaled indicators ready to be used by DEXiAqua. The method was developed by an expert consortium after multiple workshops and surveys that resulted in a consensual framework. It guarantees that, from the SIMTAP expert's perspective, the attributes considered are the most relevant to assess the sustainability of aquaculture systems. However, to prevent possible divergences between experts linked to specific systems, this framework can be adapted to the geographic, economic, social, and environmental contexts of specific case studies. However, users should use common references (i.e., indicators, thresholds, and scales) to compare systems.

5.2. Practical Implications

The method was tested on an initial case study, which confirmed the time-consuming nature of such assessment, although part of the data had already been collected. It reveals the usefulness of the developed template that automatically calculates most of the indicators and the related scales. It permits the user to have the first check on obtained values and prevent some errors before launching the DEXi model. The case study also confirmed the ability of DEXiAqua to assess overall sustainability and to provide detailed indications for improvement. It can identify which parameters to focus on in a complex attribute tree of the system to improve the overall sustainability. Again, the template allows to quickly test modifications on the input data and their implications on sustainability.

5.3. Limitations and Future Research

Future steps will include applying the method to multiple systems. This will include an IMTA system and a reference system in each of France, Italy, Malta, and Turkey. Beyond their intrinsic objectives (to compare IMTA systems to those that already exist), the assessments will help determine how to adapt DEXiAqua to geographic contexts. They will also provide additional information to analyze the sensitivity of DEXiAqua. The method will benefit from these multiple assessments and will be adapted until the end of the project to apply it to additional case studies. It would also benefit from being tested by experts on aquaculture systems. Finally, the use of fuzzy logic should be investigated in the future principally in order to minimize the knife-edge effect of the use of thresholds as performed by the CONTRA model [38].

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13147779/s1. Supplementary file S1: Python scripts for the sensitivity analysis; supplementary file S2: Indicators for DEXiAqua; supplementary file S3: Synoptic views of the three branches of sustainability; supplementary file S4: Input data for the case study; supplementary file S5: Scaling result for the case study; supplementary file S6: Synoptic view od the case study results.

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