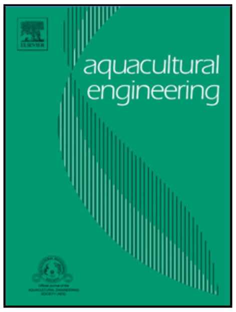
Badiola M, Mendiola D & Bostock J (2012) Recirculating Aquaculture Systems (RAS) analysis: main issues on management and future challenges, *Aquacultural Engineering*, 51, pp. 26-35.

NOTICE: this is the author's version of a work that was accepted for publication in Aquacultural Engineering. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Aquacultural Engineering, [VOL 51 (2012)] DOI: http://dx.doi.org/10.1016/j.aquaeng.2012.07.004



Title: Recirculating Aquaculture Systems (RAS) analysis:
main issues on management and future challenges

Author: Maddi Badiola Diego Mendiola John Bostock

PII: S0144-8609(12)00060-X
DOI: doi:10.1016/j.aquaeng.2012.07.004
Reference: AQUE 1645

To appear in: *Aquacultural Engineering*

Received date: 4-5-2012
Revised date: 28-6-2012
Accepted date: 2-7-2012

Please cite this article as: Badiola, M., Mendiola, D., Bostock, J., Recirculating Aquaculture Systems (RAS) analysis: main issues on management and future challenges, *Aquacultural Engineering* (2010), doi:10.1016/j.aquaeng.2012.07.004

Abstract

The main issues for Recirculating Aquaculture Systems (RAS) are analyzed, in order to lead to better solutions for future managers, identifying possible areas for improvements and future challenges for the industry. RAS-based production companies, researchers, system suppliers and consultants were interviewed separately, in order to gain an overall understanding of those systems and what developments could assist, in a positive way. Answers and subsequent analysis identified as significant barriers: poor participation by the producers; a disincentive on sharing information; and a lack of communication between different parties. The main issues are poor designs of the systems, as many had been modified after a previous approach was unsuitable; and their poor management, due mainly to an absence of skilled people taking responsibility for water quality and mechanical problems. As RAS will play an important role within the future of aquaculture, their enhancement is needed. Key priorities are the necessity to improve equipment performance, through researching at a commercial scale and further work on the best combinations of devices for each particular situation. Additional recommendations are for a specialized platform, to share knowledge on RAS, together with a more indepth and distinctive education programme.

Keywords: Recirculating systems, design, analysis, operation constraints, system management, recirculation challenges.

Highlights

- RAS companies, researchers and consultants all over the world were surveyed
- Poor system designs, water quality issues and mechanical problems are the main constraints.
- 50% of the surveyed companies have been rebuilt or redesigned due to RAS system´s failure.
- More than 8 years are need to get back initial investment
- In the future, information platforms, their availability and specialized education will be required

Recirculating Aquaculture Systems (RAS) analysis: main issues on management and future challenges

Maddi Badiola[1], Diego Mendiola*[1], John Bostock[2]

[1]: AZTI-Tecnalia. Marine Research Division. Herrera Kaia; Portualdea, s/n; 20110 Pasaia, Spain.

[2]: Institute of Aquaculture, University of Stirling, Stirling FK9 4LA, UK.

*Corresponding author:

Diego Mendiola

Present address: AZTI-Tecnalia. Marine Research Division. Herrera Kaia; Portualdea, s/n; 20110 Pasaia, Spain

Telephone: (+34) 617 46 65 88 Fax: (+34) 94 657 25 55

dmendiola@azti.es

1. Introduction

The lack of space for expansion and new sites (due to competition with other uses and interests), limited fresh water availability, and concerns over pollution are considered as key obstacles for further expansion of conventional cage-based and flow-through (FTS) aquaculture systems. Therefore, European countries –mainly existing aquaculture producers – United Kingdom, Ireland, Italy (Eurostat, 2010) and Norway (Eurostat, 2011; Bellona – AquaWeb, 2009) have promoted Recirculating Aquaculture Systems (RAS) as one of the possible solutions and opportunities to further develop aquaculture. This approach is encouraged also in the European Commission strategy documents (COM, 2002; 2009).

Several countries among the old continent are moving into RAS systems, justifying their change with sustainability reasons.

In Denmark, for example, which is the “fifth largest exporter of fish in the world” (Ministry of Food, Agriculture and Fisheries, 2011), the aquaculture industry is “characterized by recycling systems” (Waterland, 2011). The governments’ strategy (Operational Programme for the Development of the Danish Fisheries and Aquaculture Sector 2007-2013) is to increase aquaculture production, whilst reducing nutrient discharges (e.g. nitrogen levels) (Ministry of Food, Agriculture and Fisheries, 2007). Here, aquaculture is predominated by the rainbow trout (*Onchorhynchus mykiss*) culture. A recent report (Jokumsen and Svendsen, 2010) on the technologies used in Denmark, for the culture of this species, showed that RAS are increasingly important. Roque d´Orbcastel et al. (2009) noted that “more than 10% of trout was produced in RAS”, as they are considered one of the most sustainable methods of fish production. Already, in the early part of the Century, Blancheton (2000) cited that many of the hatcheries within Europe were using RAS systems, while research projects were under development.

Another clear example is the production of Atlantic salmon, the highest value species for European aquaculture (production of nearly one million metric tonnes, Tm, with a production value of around 575 million € [European Commission, 2011]; this is mainly produced in Norway, Scotland and the Faroe Islands (Bergheim et al., 2009). The tendency for future developments in the northwest Europe is to change current flow-through hatchery systems into RAS; in the Faroe Islands, 100% of that production is carried out by RAS (Bergheim et al., 2009).

Consequently, a clear example of new aquaculture industry development region is located the Basque Country (an autonomous community, located in the north of Spain). Here, the environmental conditions are not suitable for cage farming and a lack of space along the coast is an obstacle. Thus, RAS systems have been presented within the “Strategic Action Plan for Aquaculture Development 2009-2014”, as the main option to develop the fish-farming industry (Gobierno Vasco, 2008). More recently, in 2010, a new RAS facility was opened in the region (within the European Fisheries Funding Programme [EFF]).

Although, as shown in European countries, the development of RAS is positive (in 1986 just 300 tonne/year were produced in the Netherlands whilst, in 2009, the different countries contributed to the production of more than 23,463 tonne/year [dates derived from Martins et al. 2010]), many systems had been affected badly by poor management or by poor designs. Both advantages and disadvantages have been published by several authors, over the years (e.g. Liao and Mayo, 1974; Sheperd and Bromage, 1988; Blancheton, 2000; Lekang, 2007; and Timmons et al., 2009). However, few publications have arisen regarding the issues and constraints the systems experience, with respect to management.

RAS systems were developed as a technology for intensive fish farming, used mainly when water availability is restricted: they enable up to 90-99% of the water to be recycled, through the utilization of many different components. These systems allow the operator greater control over the environmental and water quality parameters, thus enabling optimal conditions for fish culture (Heinen et al., 1996). In contrast, high capital and operational costs as well as the requirement for a very careful management and difficulties in treating the diseases (e.g. Schneider et al., 2006), are the main limitations. Moreover, having water in continuous reuse, constant pumping of new intake water is needed, leading with elevated electricity costs i.e. the higher the water reuse, the more elevated will be the costs (Shepherd and Bromage, 1988). Thereafter, RAS systems are not simple systems; they are technology-biology interaction systems, requiring performance monitoring (Lekang, 2007). They have benefitted from continuous development (from the simplest path of water treatment until the most sophisticated process) (Muir, 1982; Rosenthal, 1993); nowadays, they are considered “high-tech” methods.

Within the above framework, most of the research has been directed to improving particular devices, as well as the one best performing individually (e.g. biofilters [van Rijn, 1996; Eding et al., 2006; and Summerfelt, 2006] and solids removals [Piedrahita et al., 1996; Cripps and Bergheim, 2000; and Summerfelt and Penne, 2005]), to compare different techniques (Roque d´Orbcastel et al., 2009; Pfeiffer et al., 2011) and to design entire systems based on particular assumptions (Morey, 2009). Such approaches almost always focus upon their environmental impact (latest publication Martins et al., 2010) and on pilot-scale trials. In the same way, little has been done to describe potential risks (e.g. Hrubec et al., 1996) and issues (reported failures are for inadequate biofilters use, power failure, bad alarm connection, poor marketing approach and off-flavour problems in the harvested fish), whilst managing the system, and how all the components can be combined together. Most of the conclusions and studies relate to specific situations. However, there are not identical systems and it is difficult to use one particular example to construct a good performance RAS (Piedrahita et al., [1996] cited this output of a workshop on Aquaculture Effluent Treatment Systems and Costs, held at Stirling Universty [June, 1994]). The understanding of the system is one of the key factors in its management, as this requires interaction between engineering and life organism biology and husbandry. One of the most critical parameters reported in intensive farming has been the oxygen demand and its availability (concentration). While this decreases, other unwanted water quality parameter concentrations increase (Piedrahita et al., 1996); and their balance can be achieved only through correlated work between good designs (engineering) and on understanding of animal behavior (Lekang, 2007). The work is more accurate and a profitable work if all parameters are monitorized and followed strictly, during the entire production cycle.

The core objective of the present study is to analyze the most important issues, taking/abstracting information/knowledge and experience from both successful and closed companies, from researchers and aquaculture consultants, as well as from the system designers. This overall view will aid in the understanding of where improvements can be made, that will benefit the entire industry.

2. Methodology

A survey was undertaken in such a way as to obtain both quantitative and qualitative data, seeking to analyze both internal and external opinions and experiences surrounding RAS application within the industry. Within the framework of new technologies gaining more importance, a wide range of communication channels were used to reach different interviewees. The idea was to conclude with an overall point of view of the questions presented, in order to obtain heterogeneous results and discussion. Two sides of the industry were distinguished: RAS system companies and producers; on the other hand researchers, consultants and manufacturers. Therefore, two kinds of questionnaires were developed and used, as appropriate, for each of the interviewees; a RAS system questionnaire and a research questionnaire.

The first was directed towards to reference aquaculture production companies. Its main objective was to investigate the practical and implementation side of the industry. Questions about problems that had affected their system (e.g. types and sources of problems) were asked, how they were solved or managed and how these influenced production and economic performance. Since system components and design were/are selected depending upon the site, cultured species, type of water, and life stage, an appreciation of overall system design and context is essential to link the cause and its subsequent effect. General data such as cultured species, produced life stage, system components and more detailed data such as production or working procedure, systems´ monitoring level, disease issues, detailed problem examples and economic impacts were sought. In the last part, opinions were asked on future expectations and development plans.

The second questionnaire was developed to investigate the opinions and experience of designers, suppliers and other advisers on RAS, who are not managing commercial-scale production systems; thus, compare and contrast diverse ideas and approaches for the future. More subjective than the previous one, respondents were expected to draw on knowledge of a wider range of systems, rather than one specific system. The recipients were asked: which of the component was most difficult to handle for a manager and why; the most common and the worst failures in a RAS system, and their proposed solutions; and, finally, the needed (but lacking) information around this kind of system.

Diverse methods were used to involve as many people as possible, with different opinions, involved in the survey. The RAS questionnaire was launched online via “Bristol University Survey Service” as part of the university´s utilities Companies were approached to participate in the survey, after searching for them via the Internet, e.g. viewing each country´s government´s websites and approaching different experts within the industry. At the same time, a link to the survey was posted in several social networks and websites (e.g. European Aquaculture Society -EAS- membership forum, LinkedIn, Aquaculture hub, University of Stirling – Institute of Aquaculture website front-page). In addition, confidential interviews were undertaken together with production managers from different farms in different countries and to experts with different backgrounds (e.g. consultants, researchers, and system suppliers).

Previously distinguished groups, both producers and experts, were analyzed separately: the “Bristol University survey service” was used to analyze the RAS questionnaire, whilst NVivo 9 software was used to analyze the research questionnaire. The "Bristol University survey service" recorded the results in the system, for subsequent analysis of the data. The service permits making both quantitative (e.g. the percentage of people who responded to each option) and qualitative analyses (e.g. cross-tabulate results between two specific questions, cross-tabulated results between a specific question and the whole survey, or additional analysis like word clouding - up-scale words from a certain question answers depending its important, weighted by the number of times appeared -). The interviews, once recorded, were transcribed and exported to the NVivo 9 program. This served to analyze and identify the main ideas, permitting the classification of data following different criteria (e.g. the role in industry or type of working field), summarizing all the answers for each of the questions and creating "mind maps" for more visual and easy to understand results.

3. Results

Replies from aquaculture production companies were not as expected; although, overall, they represent the highest percentage (Table 1). Such numbers make clear a) the excessive confidentiality that surrounds the RAS system industry (regarding to their design and operational methods); and b) the lack of interest supporting the study, as many refusals to cooperate were received. The lack of a specific data compilation of RAS systems companies in Europe (corroborating the statement made by Martins et al., 2010) made it difficult to locate and contact them all.

In the figure 1 are shown the sampled top reference companies differentiated by nationality whilst in the figure 2 the distribution is made depending on the specie the companies' culture or produce. The highest number of companies is from the UK, followed by both Spain and France. These data could assist in updating the research carried out by Martins et al. (2010). The number of companies producing tilapia was the most common (6 companies, representing 37.5%). Thus, 75% of the companies use freshwater (e.g. river or lake water, municipality water, rain water), 18.75% seawater and 6.25% brackish water (depending on species and source of water). Due to the wide variety of species produced, but only limited companies for each, no comparison can be made in terms of management procedures, as well as in terms of failure reasons and financial aspects. Fish life stage is one of the most significant contrasting factors, when classifying and describing different kinds of RAS companies. Thus, in Figure 3 respondents are distinguished in terms of the life stage of their culture. From this Figure it can be concluded that most of the production companies that answered the survey are on-growing fish, followed by hatchery farms. Among the 12 on-growing farms, 2 were closed presently whilst one would be reopened in the near future due critic engineering failures. Of the others, the systems of 5 companies were set up as new projects whilst 4 were change to improve the previous systems. The main changes were due to redesigns, from flow-through (FTS) to RAS; also, to aquaponic systems, for different reasons. Finally, the companies are profiled in terms of the RAS system components used. As can be seen, in Figure 4, biofilters and pumps are parts of all systems and solids removal and oxygenators are components for nearly all the systems (94.1% and 88.2%, respectively). It can be seen that skimmers (64.7%) and disinfection devices (ozone is used mainly in all of the seawater companies) are not very usual and neither are denitrification devices (just in 25% of freshwater systems). Within each component category there are different types: e.g. trickling biofilters are the most expanded type of biological filtration devices and drum filters are the most expanded ones for solids removal. For carbon dioxide (CO_2) removal, ventilators, airlifts and the same biofilters are being extensively used. Heating and cooling methods vary from the use of traditional heaters (gas boilers) and solar panels (photovoltaic panels providing electricity and then used for heating or cooling), to the recovery of energy from the freezers installed in the companies and the use of submerged pumps (also considered a source of heat).

3.1 Main issues of RAS systems

As cited above, the technology is very dependent upon the life stage of the cultured animal, e.g. it is different to manage newly hatched or small size animals; this is why on-growing and hatchery are considered separately, from here onwards. Cross-tabulating certain questions of the questionnaire it was shown that issues are dissimilar between them. In any case, it is difficult to assess the exact cause of each problem, as the information provided by the producers is not sufficiently detailed and different sources could result in the same consequence. For instance, water quality issues caused mainly by mechanical problems are usual in hatcheries (3 out of 3), whilst badly designed equipment is the most common cause of problems for on-growing systems (5 out of 6). Moreover, whether referring to biological or management problems (i.e. internal or external causes), the answers obtained reveal that issues arise from an initial poor design. For researchers and consultants, clustering the most common issues cited indicates in this order, the main weaknesses: wrong system approach (i.e. inaccurate parameter design calculations, and being too optimistic); inappropriate management (including lack of training); maintenance issues (poor water qualities achieved); and poor system designs (e.g. equipment selection). Likewise, the lack of response to unforeseen circumstances is also a common issue.

Water-quality issues sources are difficult to assess, as they are produced by different causes: e.g. poor approach of the overall system and production quantities (e.g. lower stocking densities than the real ones used for the calculations); equipment failure (in most of the cases due to bad designs); or poor maintenance of the system. Among all the water parameters, ammonia (appearance in 49.06% of the answers), carbon dioxide (25.67%) and oxygen (31.25%) are, for the managers, the most difficult ones to control (results obtained from word frequency query, whilst examining which parameters are monitorized and which of them are the most difficult to control). These are all caused by: (I) a considerable lack of knowledge (followed by complex designs, which is inversely related) and (II) deficient or poor training of the managers; not being able to maintain water quality parameters (with an influence in the performing of both biofilter and solid removal device) (Figure 5). Figure 5 presents the answers obtained from researchers and consultants (based upon their experiences). Managers of the farms attribute these problems to incorrect specifications in the case of the solids removal devices, together with undersized biofilters that rapidly clog. Adding the difficulties of managing certain devices, to the inadequate knowledge and skills of the managers, the final result is an imbalance of water parameters, damaging both cultured fish and the water´s treatment components.

Oxygen and carbon dioxide are also risk factors. Gas imbalance in the system is due to bad designs (e.g. wrong design calculations, inefficient gas stripper, or lack of it) influencing directly carbon dioxide concentrations. Nevertheless, the most common water quality issues (stated by 14/16 companies surveyed and noted by more than two thirds of the researchers and consultants interviewed) were solids in the water, which impact upon the overall system. Most experts consulted agreed that if they are not removed efficiently from the system, the biofilter is affected and does not function properly (i.e. it gets blocked/clogged); thus, nitrification is not completed, leading to high concentrations of toxic compounds (ammonia and nitrite), affecting fish health and welfare.

Likewise, poor initial design, or incorrect assumptions such as assuming lower stocking densities than are actually used, or modeling with simple equations (e.g. kg of oxygen needed per kg of feed), having a substantial impact on final water quality and operational costs (i.e. fish poorer food conversion ratios, increasing solids concentration, ending up with a clogged biofilter). As stated by researchers, RAS systems do not only contain populations of fish, but their effective operation is also contingent upon a thriving population of bacteria: these bacteria consume oxygen and produce waste, whilst their metabolism is vital to the success of the system. This fact is often overlooked by RAS companies; and as such it is one of the worst mistakes leading to failure of a RAS system.

Mechanical problems are also common in hatcheries and on-growing systems, derived, in the first place, from bad design or bad management (i.e. resulting from unexpected conditions). This pattern is created because consultants and suppliers specify that the cheapest equipments are used to meet the demands of the producers for low capital investments. The solutions given for this problems are quick repairs and in last resort replacements. Indeed, this extra capital expenditure due to rapid repairs and replacement were the reason that leaded to some farms to close the business operation. Typically, the most replaced devices, due to a RAS failure, are disinfection devices (i.e. ozone and UV), pumps and biofilters (e.g. 50% of the times when a biofilter or a pump has been replaced, it was for a RAS deficiency, 75% for O_3 and 66% for UV devices). Moreover the connecting pipework and drainage pipes had also been reported as being problematic, undersized and not effectively designed (e.g. slope), respectively. Issues included here directly affect the oxygen amount in the tanks. Another effect is that lower water velocities cause the settlement of solids and/or growth of weed, i.e., compromising the water quality. As an outcome, eleven out of seventeen companies were rebuilt or redesigned completely, following their initial installation; 50% of them due to deficiencies in RAS, whilst the other 50% mainly to extend the production capacity.

With reference to system components, according to few consultants surveyed, biofilters and solids removal are by far the most important, in order to optimize water quality (i.e. for healthy fish and good system performance). However, as the solids concentration increases within the system, increasing fish susceptibility to stress (higher FCRs are obtained, with slower growth) and increasing carbon dioxide concentrations to risky levels, the CO_2 removal becomes a relevant aspect, sometimes not considered, at the designing stage; CO_2 devices are missing in nearly half of the systems, as unforeseen situations and risks are ignored by the designers or installers, when calculations are. An inadequate control over water temperature and the absence of pH control are also identified issues for some systems; among the mentioned causes the inadequate calculations, perhaps based upon laboratory and small scale or trials results are highlighted. One of the most reported issues, particularly affecting on-growing systems (as they produce fish directly for the market), is off-flavors´. Five out of seven on-growing companies reported that this has been a problem, although the product is depurated, over between two days and six weeks, before sale.

Regarding emergency systems (including both alarm and emergency equipment), two thirds of the consultants agree that poor backup systems still remain in many production companies (the main reason being the desire to have a low initial investment). In terms of emergency equipment, nearly 40% of on-growing producers have just one biofilter and 50% just one solid removal device; this illustrates that little is invested on them. Moreover, in order to decrease the investment, consultants agree that fewer tanks than are really needed (e.g. for the daily procedures such as grading, harvesting and cleaning) and smaller pipe diameters are installed frequently; these compromise daily tasks and increase the probability of failure. Regarding alarms and asking consultants about them, 15 out of 18 agreed that poor alarm networks are in place (in relation to poor or non-maintenance of the installed systems and to a lack of a proper alarm system). Overall, the survey results show that hatcheries have better backup set-ups than on-growing systems due, probably, to the higher added value of the cultured products.

As stated before, unsuitable designs are frequently reported as a common reason of failure. System design relies often upon engineers with a limited comprehension of the science of RAS. Furthermore, the data provided by the managers are calculated optimistically, so designs may not be realistic. The results from table 2 showed that it is notable that there is a similarity between problems caused by equipment, design and RAS system installers/designers. 70% of the systems designed by an external or separate company had problems at some point, whilst none of the farms designed by the final operators reported equipment failures. As reported by the surveyed participants, consultancy support after the implementation of RAS system, from an independent designer, is not as good as is needed (conclusion, 60% of the companies confirm not having an adequate after-sales assistance and support). This is endorsed by the interviewed consultants, who say that many suppliers promise consultancy support availability after selling the product but, in reality, this is limited. Therefore companies need to pay high fees for advice and problem solving.

When asking company managers about information available or presently published literature about RAS systems, 9 of them agreed that there is a need for more data and accessible literature; however, they remarked also that this will not be the only solution mostly because, as well as theorical knowledge, experience and practice are needed. 82.4% of the companies agree that there is a necessity for better training, as the current provision is lacking. Moreover, consistent with the views with consultants, all of them admit that it is one of the most important aspects of implementing a RAS. Figure 6 shows the areas the information is lacking; hence, where the research should be targeted.

Conversely, looking at the answers of researchers and consultants, there is no need for more information or literature on individual components, what is needed is the improvement of the overall approach to RAS system design (not just technical feasibility, but also economic feasibility) and improvements in design calculations (being more realistic and less idealistic and having in mind that the system can go wrong). More specifically, among the researchers some particular aspects for improvement were mentioned: the understanding of nitrification and, in particular, denitrification, management of produced sludge and the control of off-flavours. Both of the groups agree that there are many people with knowledge in general aquaculture but not in RAS in particular; consultants and researchers blame this on the lack of communication between universities, R&D facilities and companies. It was also agreed that training has to include not just basic water reuse system´s management, but also develop an understanding of the interactions between biology, chemistry, physics, engineering and economics.

3.3 Challenges and future adoption of RAS systems

Finally, financial aspects of RAS were the major issue in response to asking about the challenges to wider adoption in the future. This observation was reinforced by the companies, showing that the financial performance is inadequate in more than 80% of the cases and there is inadequate return on the capital employed, i.e. more than 8 years are needed, on average, to get back the initial investment (Figure 7). Therefore, there is a need to reduce costs per unit of production capacity and operating costs. The development of new energy sources and the reuse of system´s byproducts are the main ideas for future development (these appear in 85% of the interviewees answers, as possible solutions).

4. Discussion

The future of aquaculture is to produce fish in a more sustainable way, because demand is likely to increase (FAO, 2010) and policy frameworks are becoming more restrictive environmentally. However, RAS technology should secure the control of water quality parameters and the optimization of rearing conditions at the lowest environmental cost. Despite that, the benefits of RAS will depend upon the type and where they are set up. A full control of (I) water quality parameters and (II) water treatment units' performance, to achieve biosecurity levels and reduce environmental impacts, should represent the main benefit of RAS. Nevertheless, their adoption in the future will be determined by the response of industry to the challenges that they face. In the first instance, research and improvements, in terms of individual devices, should be directed towards commercial scale aquaculture, obtaining more reliable and useful data. Their operational systems will need to be better understood, in order to move towards a standardization of the industry. Moreover, in terms of improving their management and having more efficient and less failure prone systems, more specialized and highly capable people will need to be trained. By now, more than 50% of the companies surveyed have been rebuilt or redesigned due to RAS system´s failure. As stated within this contribution, many are the factors and interactions, from the designing stage through the product quality, which can affect both the production success and the subsequent economic profitability of the selected business concept using RAS technologies (Figure 8).

4.1 Main issues of RAS systems

As reported, solids management and biofilter operation and management are the most difficult tasks in a RAS, constituting the main reasons for system failures. Treatment technology is developed already but how to integrate it all together in the optimum way is likely missing. Rather than looking for better and more complex designs which can often be more difficult to manage, the necessity is to understand which factors are key in each particular system (e.g. fish requirements, energy requirements, water availability). Accordingly to McKindsey et al. (2006), in order to understand each system´s limits, it is required to define physical, environmental, production and social carrying capacity issues; this argument will ensure consistency in meeting the required sustainability needs of the commercial production systems using RAS.

Suspended solids are the source of most of the water quality issues, as they have an important impact on the performance of nearly all of the other RAS components as shown by the present study; therefore, their management is fundamental for the systems good performance as stated already by Han et al. (1996). A biofilter is affected directly if suspended solids are not removed efficiently from the treatment loop (e.g. Jokumsen and Svendsen, 2010); it becomes clogged, decreasing its specific surface area (SSA)[1] and, thus, the quantity and the viability of nitrifying bacteria. Moreover, as the solids concentration increases within the system, water parameters are modified and these changes are the causes of stress in both cultured fish and nitrite-oxidizing bacteria (Malone and Pfeiffer, 2006; Emparanza, 2009), hampering their performance due to their susceptibility to changeable situations (Singh et al.,

---

[1]: a parameter to evaluate and compare different biofilters and the surface where bacteria

1999). At the same time, inadequate solids removal creates a competition between both heterotrophic and autotrophic bacteria (Satoh et al., 2000; Zhu and Chen, 2001; Leonard et al., 2002; Ling and Chen, 2005; Michaud et al., 2006), increasing ammonia levels in the water amongst other things. Apart from the biofilter, other equipment, such as ozone devices and pumps, are also influenced. Ozonation becomes less efficient as the solids concentration increases (e.g. when feeding spikes occur during the cycle) (Summerfelt et al., 2009) in the water; this necessitates a longer contact time to destroy particulates, which can lead to production of more dangerous O_3 byproducts as the concentration increases. At the same time, suspended solids generate mechanical issues in both of the equipments cited, which can lead to the need for repairs and, thus, additional costs, as reported in the present study. Therefore, suspended solids extraction from the system has to be rapid and with as little breakdown as possible, by not treating them harshly (McMillan et al., 2003; Summerfelt et al., 2001). Further research should be targeted at improving their removal using different kinds and combinations of methods; nevertheless, this will need to be at a commercial scale. However, any combination of the components must be suitable for the farmed fish species and their particular water quality requirements, as well as in accordance with the cost efficiency. A good solids removal management strategy will be necessary also to control the microbial community of the system, thus ensuring a properly functioning biofilter. Accordingly, this has begun to be investigated in recent years by Davidson and Summerfelt (2005), Couturier et al. (2009) and Ray et al. (2010), who showed that a “polishing unit designed specifically to remove fine particles” is needed, in order to capture up to 95% of the solids and, therefore, improve a system´s efficiency; however, in those experiments, the component´s contribution to the whole system´s performance varied, showing different results and requiring further research into the future. However, as reported by different authors, the use of micro screens drum filters seem to be a cost-effective type of solids filters in the classic range of 40 to 90 micron filtration (Carlsen 2008).

Together with solids removal devices, biofilters constitute a non-less important and difficult device for management. A good understanding of both biofiltering operation and maintenance requirements is essential. However, as reported by different authors and also concluded herein, one of the reasons for biofilters being difficult to manage is because investigations until now have been focused upon laboratory scale trials, whilst it has been shown that commercial scale RAS waste (more feed inputs, creating higher organic carbon concentrations) is very dissimilar to that produced in pilot scale (Zhu and Chen, 1999; Losordo and Hobbs, 2000; and Ling and Chen, 2005; Emparanza, 2009 and Guedart et al. 2010; 2011). Thus, as 85% of the interviewees support, more information about the impact of organic compounds on the biofilters is needed in commercial scale systems, as there is only limited data available. Since a biofilter´s characteristics determine the maintenance requirements and management techniques needed the search for standards to classify them and provide specific information to the industry is very likely what the market (companies and consultants) requires. Several authors have addressed already this need (Drennan et al., 2006; Malone and Pfeiffer, 2006; and Colt et al., 2006), but once again, little practical on-farm research has been undertaken (Suhr and Pedersen, 2010; Guedart et al. 2010, 2011). Apart from this, biofilters rely on many parameters (Chen et al., 2006) and a rapid and accurate actuation is essential, in case of an unexpected imbalance. This approach requires strict working protocols and experienced and knowledgeable management as reported in the present study. There are many complex factors that interact during the commercial operation of a RAS and its biofilter. Daily procedures, such as tank cleaning, grading and harvesting can affect biofilter´s efficiency because water parameters are modified, affecting the hydraulics and causing system fluctuations; similarly, when fish are harvested or removed from the system for sale, the biomass accordingly declines. Furthermore, the biomass is changing continuously, fish continue to grow whilst more are introduced; this leads to more feed input, higher temperatures (as there is higher metabolic activity), increased carbon dioxide and ammonia production and less oxygen availability (more competition), slowing growth. Therefore management requirements become modified. Thus, managers have to reorganize gradually, to take into account abrupt changes within the biofilter and try to lessen their impacts otherwise both living bacteria and cultured fish will become stressed, leading to uncontrolled system parameters and high fish mortality rates. Some possible management procedures for salmonids, on a commercial scale were presented by Emparanza (2009); it was concluded that feed input, water exchange and stocking density are the variables with the most impact. One reported solution is could be the oversizing of biofilters, to ensure they are more flexible in response to changes; however, this formula demands also higher investments. So that a suitable balance can be reached, calculations need to be more realistic and less optimistic (i.e. including a margin of error) whilst cost-effectiveness needs to be a requisite, in relation to the four types of carrying capacities (physical, production, ecological and social) of the system (McKindsey et al., 2006). Finally, the person in charge should always be able to anticipate required system modifications, understanding relationships and interactions among the parameters, cultured fish and external outputs (i.e. feed, oxygen, energy and water).

As carbon dioxide is produced by fish, its concentration increases where higher stocking densities are used; it causes “uncomfortable situations” in fish, eventually affecting the whole production. However, as stated by companies, equipment for stripping this particular gas (e.g. packed column, agitators) are not used widely in the companies, mainly due to a wrong or poor approach to system design and higher investment requirements. In reality the appearance and subsequent monitoring of abnormal CO_2 concentration could help to more rapidly identify other problems (Pfeiffer et al., 2011), assisting the better management of the system.

Although off-flavors are not the most common reason of failure in the industry, they can be a motive for bankrupt, because no profits are obtained if fish do not meet consumer demand. It is known that both geosmin and 2-methylisoborneol (MIB) are responsible for this "earthy" and "musty" taste in the products (Tucker, 2000; Howgate, 2004; and Houle et al., 2011) but how to remove them, or how to decrease their occurrence, is still under investigation (Schrader et al., 2010) without much success. Guttman and van Rijn (2008) have proved that having anaerobic conditions within the system could be a possible solution for the mitigation of this problem. Likewise, denitrification devices, although presently not very common, are being used where high levels of nitrate, high stocking densities and high levels of C/N interact (van Rijn et al., 2006). Thus, adding a non-aerobic denitrification stage after the aerobic nitrification (i.e. biofilter) could likely mitigate both water quality and off-flavors issues at the same time; however, this will need further investigation.

4.2- Challenges and future adoption of RAS systems

One of the greatest reported constraints of RAS is the investment required and the long pay-back periods (on average 8 years). RAS are frequently not economically viable; "encouraging technology" is inevitable, but there must be an economic reason, in relation to an overall "market-need" oriented perspective of the system that ensures technically feasibility as a prerequisite to be economically viable. A good market or social study is needed, in order to meet with the actual demand, planning an affordable and realistic production goal. Thus, the first requirement is a reliable operation followed by low operating costs. Both conditions will aid recover more rapidly from the first investment: the first obtaining a stable production and, thus, profits; and the second providing a higher margin for the return. Some possible ways or solutions, as given by some of the interviewees, to make these systems "cheaper" are listed below; however, they will need to be investigated further, in terms of operational management and economical viability:

- Energy efficiency, using less and reusing energy where possible. Reducing pumping head and improving the biofilter´s performance for instance, means less energy will be needed (Jokumsen and Svendsen, 2010).

- Recovering wash water from the drum filter backwashing e.g. using flocculants (currently under investigation) will reduce the amount of intake water, decreasing environmental impact and reducing pumping costs.
- Introduction of new compartments such as algal and for aquaponics production to (I) decrease environmental output, (II) valorize nutrients and detritivores taking advantage of produced byproducts such as carbon dioxide and (III) generate secondly products to a major economical input.
- The implementation of a “hybrid technology of biofloc technology (BFT) and RAS” as Azim and Little (2008) suggested. A more recent study showed that BFT could help environmental and economic sustainability of RAS by reducing the feed cost (Kuhn et al., 2009).

It is generally accepted that Europe has the advantage of having the technology and the knowledge needed to set up RAS (COM, 2009), but this technology is more than just turning an “on/off” button and leaving it to run; it takes time to learn how to manage it. The systems are complex, in terms of understanding how they need to be handled in each particular operation situation; they depend upon many parameters which, in turn, depend upon the performance of each of the constituent parts. As stated by the interviewed participants, people with the responsibility of managing recirculation systems should be trained with functional skills, within university educational programs and on further practice or internships within research and/or participative production companies.

Fish farming is necessary and more will be needed in the future. Hence, RAS systems will continue to develop, but their improvement cannot be achieved if there is no communication within the industry (involving producers, suppliers, researchers and consultants). Furthermore, it is well known that the lack of information is due to a lack of governance (e.g. APROMAR, 2010; Scottish Executive, 2003), together with and insufficient collaboration within different work areas in aquaculture. Thus, as concluded for this study there is a disincentive for communication at a commercial level, as well as a fear of reporting “bad news of failures” to the public. Nonetheless, knowledge of RAS control and management techniques are gained with experience and, as has been demonstrated, a knowledge of the technical or engineering part of the system does not always lead to success. Moreover, this study has shown that suppliers and producers do not agree, when requesting industry´s point of view, revealing evidence of individualism. It is considered (and confirmed hereing) that sharing experiences and issues (without compromising on confidential data), can be beneficial for all parties. This study has confirmed also that social networks are useful communication channels and they are nowadays the best way to bring the people studying on RAS together.

Acknowledgements

This work would not have been possible without the assistance of several relevant experts from: (i.) IRIS, International Research Institute of Stavanger AS, Norway; (ii.) IFREMER, Aquaculture, Languedoc-Roussillon, France; (iii.) DTU, National Institute for Aquatic Resources, Hirtshals, Denmark; (iv.) University of Stirling, Institute of Aquaculture, Stirling, U.K; (v.) Cornell University, Biological and Environmental Engineering Department, Ithaca, USA; (vi.) Chalmers University of Technology, Gothenburg, Sweden; (v.) Freshwater Institute, Shepherdstown, West Virginia, USA; (vi.) and a number of relevant European companies. Professor Michael Collins (SOES, University of Southampton, UK & University of Basque Country) critically reviewed an early draft of the manuscript. This work was supported by the Department of Education, Universities and Research of the Basque Government. Finally, this paper is contribution nº 575 for AZTI-Tecnalia (Marine Research Division).

References

- APROMAR, 2010. La Acuicultura Marina de Peces en España, 2010. Cádiz (Spain) APROMAR.
- Azim, M.E., Little, D.C. 2008. The biofloc technology (BFT) in indoor tanks: Water quality, biofloc composition, and growth and welfare of Nile tilapia (*Oreochromis niloticus*). Aquaculture 282, 29-35.
- Bellona – AquaWeb, 2009. Norwegian Aquaculture Production. [online] Available at:< http://www.bellona.org/aquaculture/artikler/Production_norway> [Accessed 27 June 2011]
- Bergheim, A., Drengstig, A., Ulgenens, Y., Fivelstad, S., 2009. Production of Atlantic salmon smolts in Europe – Current characteristics and future trends. Aquacultural Engineering 41, 46- 52.
- Blancheton, J.P., 2000. Developments in recirculation systems for Mediterranean fish species. Aquacultural Engineering 22, 17-31.
- Carlsen, K., 2008. Filtration in recirculation systems- particle control, in: Fish farming experts (4): Fish farming school, part 8: Filtration in recirculation – particle control. pp 33- 38. September 2008.
- Chen, S., Ling. J., Blancheton. J., 2006. Nitrification kinetics of biofilm as affected by water quality factors. Aquacultural Engineering 34, 179-197.
- Colt, J., Lamoureux, J., Patterson, R., Rogers, G., 2006. Reporting standards for biofilter performance studies. Aquacultural Engineering 34, 377- 388.
- Commission Communication 2002/511/COM of 19 October 2002 on A Strategy for the Sustainable Development of European Aquaculture.
- Commission Communication 2009/162/COM of 8 April 2009 on A sustainable future for aquaculture – A new impetus for the Strategy for the Sustainable Development of European Aquaculture.

- Couturier, M., Trofimencoff, T., Buil, J.U., Conroy, J., 2009. Solids removal at a recirculating salmon-smolt farm. Aquacultural Engineering 41, 71-77.
- Cripps, S.J., Bergheim, A., 2000. Solids management and removal for intensive land-based aquaculture production systems. Aquacultural Engineering 22, 33-56.
- Davidson, J., Summerfelt, S.T., 2005. Solids removal from a cold water recirculating system – comparison of a swirl separator and a radial-flow settler. Aquacultural Engineering 33, 47-61.
- Drennan II, D.G., Hosler, K.C., Francis, M., Weaver, D., Aneshansley, Ed., Beckman, G., Johnson, C.H., Cristina, C.M., 2006. Standarized evaluation and rating of biofilters II. Manufacturer´s and user´s perspective. Aquacultural Engineering 34, 403-416.
- Eding, E.H., Kamstra, A., Verreth, J.A.J., Huisman, E.A., Klapwijk, A., 2006. Design and operation of nitrifying trickling filters in recirculating aquaculture: A review. Aquacultural Engineering 34, 234-260.
- Gobierno Vasco, 2008. EAE-ko Akuikulturarako Plan zuzentzailea 2008- 2013 Plan Director de Acuicultura de la CAPV. Pasaia, Guipuzkoa, Euskal Herria. [online] Available at: http://www.nasdap.ejgv.euskadi.net/r50-3812/es/contenidos/informacion/acuicultura_index [Accessed 27 June 2011]
- Emparanza, E.J.M., 2009. Problems affecting nitrification in commercial RAS with fixed-bed biofilters for salmonids in Chile. Aquacultural Engineering 41, 91-96.
- European Commission Fisheries, 2011. Aquaculture – facts and figures. [online] Available at: <http://www.ec.europa.eu/fisheries/cfp/aquaculture/facts/index_en.htm> [Accessed 26 June 2011]
- Eurostat, 2010. Fisheries statistics. Data 1995-2008. [online] Available at: <http://epp.eurostat.ec.europe.eu/cache/ITC_OFFPUB/KS-DW-09-011/EN/KS-DW-09-001-EN-PDF>[Accessed 27 June 2011]

- Eurostat, 2011. Aquaculture production – Values (1000 euro). [online] Available at: <http://www.http://appsso.eurostat.ec.europa.eu/nui/show.do>[Accessed 27 June 2011]
- FAO, 2010. The status of world fisheries and aquaculture, Rome: FAO Fisheries and Aquaculture department.
- Guedart, T.C., Losordo T.M., Classen, J.J., Osborne, J.A., DeLong, D.P., 2010. An evaluation of commercially available biological filters for recirculating aquaculture systems. Aquacultural Engineering 42, 38-49.
- Guedart, T.C., Losordo T.M., Classen, J.J., Osborne, J.A., DeLong, D.P., 2011. Evaluating the effects of organic carbon on biological filtration performance in a large scale recirculating aquaculture system. Aquacultural Engineering 44, 10-18.
- Guttman, L., van Rijn, J., 2008. Identification of conditions underlying production of geosmin and 2- methylisoborneol in a recirculating system. Aquaculture 279, 85- 91.
- Han, X., Rosati, R., Webb, J., 1996. Correlation of particle size distribution of solid waste to fish composition in an aquaculture recirculation system, in: Libey, G.S., Timmons, M.B. (Eds.), Successes and failures in commercial recirculating aquaculture. Northeast Regional Agricultural Engineering Service, Ithaca, NY, pp. 257-278.
- Heinen, J.M., Hankins, J.A., Adler, P.R., 1996. Water quality and waste production in recirculating trout culture system with feeding of a higher energy or a lower energy diet. Aquaculture 27, 699-710.
- Houle, S., Schrader, K.K., Le Francois, N.R., Comeau, Y., Kharoune, M., Summerfelt, S.T., Savoie, A., Vandenberg, G.W. 2011. Geosmin causes off- flavor in artic charr in recirculating aquaculture systems. Aquaculture Research 42, 360-365.
- Howgate, P., 2004. Tainting of farmed fish by geosmin and 2-methyl- iso bomeol: a review of sensory aspects and of up-take/ depuration. Aquaculture 234, 155- 181.
- Hrubec, T.C., Smith, S.A., Robertson, J.L., 1996. Nitrate toxicity: A potential problem of recirculating systems, in: Libey, G.S., Timmons, M.B. (Eds.), Successes and failures in

commercial recirculating aquaculture. Northeast Regional Agricultural Engineering Service, Ithaca, NY, pp. 41 – 56.

- Jokumsen, A., Svendsen, L., 2010. Farming of freshwater Rainbow trout in Denmark. DTU Aqua, National Institute of Aquatic resources. DTU Aqua report no. 219.
- Kuhn, D.D., Boardman, G.D., Lawrence, A.L., Marsh, L., Flick, G.J., 2009. Microbial floc meal as a replacement ingredient for fish meal and soybean protein in shrimp feed. Aquaculture 296, 51-57.
- Lekang, O.I., 2007. Aquaculture Engineering. 3rd ed. Oxford: Blackwell Publishing.
- Leonard, N., Guiraud, J.P., Gasset, E., Cailleres, J.P., Blancheton, J.P., 2002. Bacteria and nutrients – Nitrogen and carbon – In a recirculating system for sea bass production. Aquacultural Engineering 26, 111-127.
- Liao, P.B., Mayo, R.D., 1974. Intensified fish culture combining water reconditioning with pollution abatement. Aquaculture 3, 61-85.
- Ling, J., Chen, S.L., 2005. Impact of organic carbon on nitrification performance of different biofilters. Aquacultural Engineering 33, 150- 162.
- Losordo, T.M., Hobbs, A.O., 2000. Using computer spreadsheets for water flow and biofilter sizing in recirculating aquaculture production systems. Aquacultural Engineering 23, 95-102.
- Malone, R.F. and Pfeiffer, T.J., 2006. Rating fixed film nitrifying biofilters used in recirculating aquaculture systems. Aquaculture Engineering 34, 389- 402.
- Martins, C.I.M., Eding, E.H., Verdegem, M.C.J., Heinsbroek, L.T.N., Schneider, O., Blancheton, J.P., Roque d´Orbcastel, E., Verreth, J.A.J., 2010. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. Aquacultural Engineering 43, 83-93.

- McKindsey, C.M., Thetmeyer, H., Landry, T., Silver, W., 2006. Review of recent carrying capacity models for bivalve culture and recommendations for research and management. Aquaculture. 261, 451-462.
- McMillan, J.D., Wheaton, F.W., Hochheimer, J.N., Soares, J., 2003. Pumping effect on particle sizes in a recirculating aquaculture system. Aquacultural Engineering 27, 53-59.
- Michaud, L., Blancheton, J.P., Bruni, V., Piedrahita, R., 2006. Effect of particulate organic carbon on heterotrophic bacterial populations and nitrification efficiency in biological filters. Aquacultural Engineering 34, 224-233.
- Ministry of Food, Agriculture and Fisheries, 2007. Operational Programme for development of the Danish fisheries and aquaculture sector, 2007-2013, Denmark: Ministry of Food, Agriculture and Fisheries.
- Ministry of Food Agriculture and Fisheries, 2011. Development and innovation in fisheries and aquaculture [online] (Updated 13 April 2011). Available at: <http://www.fvm.dk/fisheries%20and%20aquaculture.aspx?ID=15231> [Accessed at 17 May 2011].
- Morey, R.I., 2009. Design keys of a recent recirculating facility built in Chile operating with fluidized bed biofilters. Aquacultural Engineering 41, 85-90.
- Muir, J.F., 1982. Recirculated water systems in aquaculture, in: Muir, J.F., Roberts, R.J. (Eds.), Recent Advances in Aquaculture. Croom Helm, London, pp. 358-453.
- Pfeiffer, T.J., Summerfelt, S.T., Watten, B.J., 2011. Comparative performance of CO_2 measuring methods: marine aquaculture recirculation system application. Aquacultural engineering 44, 1-9.
- Piedrahita, R.H., Fitzsimmons, K., Zachritz II, W.H., Brockway, C., 1996. Evaluation and improvements of solids removal systems for aquauculture, in: Libey, G.S., Timmons, M.B. (Eds.), Successes and failures in commercial recirculating aquaculture. Northeast Regional Agricultural Engineering Service, Ithaca, NY, pp. 141- 149.

- Ray, A.J., Seaborn, G., Leffler, J.W., Wilde, S.B., Lawson, A., Browdy, C.L., 2010. Characterization of microbial communities in minimal-exchange, intensive aquaculture systems and the effects of suspended solids management. Aquaculture 310, 130-138.
- Roque d´Orbcastel, E. Blancheton, J.P., Belaud, A. 2009. Water quality and rainbow trout performance in a Danish Model Farm recirculating system: Comparison with a flow-through system. Aquacultural Engineering 40, 135-143.
- Rosenthal, H., 1993. The history of recycling technology: A lesson learned from past experience?, in: Reinertsen, H., Dahle, L.A., Jorgensen, L., Tvinnereim, K., (Eds.) Fish farming technology, Balkema Publisher, Rotterdam, Netherlands. pp. 341 – 349.
- Satoh, H., Okabe, S., Norimatsu, N., Watanabe, Y., 2000. Significance of substrate C/N ratio on structure and activity of nitrifying biofilms determined by in situ hybridization and the use of microelectrodes. Water Science Technology 41, 317-321.
- Schneider, O., Blancheton, J.P., Varadi, L., Eding, E.H., Verreth, J.A.J., 2006. Cost price and production strategies in European recirculation systems. Linking tradition and technology highest quality for the consumer. WAS, Firenze, Italy.
- Schrader, K.K., Davidson, J.W., Rimando, A.M. and Summerfelt S.T., 2010. Evaluation of ozonation on levels of the off-flavor compounds geosmin and 2-methylisoborneol in water and rainbow trout Oncorhynchus mykiss from recirculating aquaculture systems. Aquacultural Engineering 43, 46- 50.
- Scottish Executive, 2003. A Strategic Framework for Scottish Aquaculture. Edinburgh: Scottish Executive. pp. 20,27
- Shepherd, J., Bromage, N., 1988. Intensive Fish Farming. Oxford: Blackwell Science Ltd.
- Singh, S., Ebeling, J., Wheaton, F., 1999. Water quality trials in four recirculating aquacultural system configurations. Aquacultural Engineering 20, 75-84.

- Suhr, K.I., Pedersen, P.B., 2010. Nitrification in moving bed and fixed biofilters treating effluent water from a large commercial outdoor rainbow trout RAS. Aquacultural Engineering 42, 31-37.
- Summerfelt, S.T., Bebak-Williams, J., Tsukuda, S., 2001. Controlled systems: water reuse and recirculation, in: Wedemeyer, G. (Ed.), Fish Hatchery Managemet. Bethesda MD, American Fisheries Society, pp. 285-395.
- Summerfelt, R.C., Penne, C.R., 2005. Solids removal in a recirculating aquaculture system where the majority of flow bypasses the microscreen filter. Aquacultural Engineering 33, 214- 224.
- Summerfelt, S.T., 2006. Design and management of conventional fluidized-sand biofilter. Aquacultural Engineering 34, 275-302.
- Summerfelt, S.T., Sharrer, M.J., Tsukuda, S.M., Gearheart, M., 2009. Process requirements for achieving full-flow disinfection of recirculating water using ozonation and UV irradiation. Aquacultural Engineering 40, 17-27.
- Timmons, M.B., Ebeling, J.M., Piedrahita, R.H., 2009. Acuicultura en Sistemas de Recirculación. Ithaca, NY: Cayuga Aqua Ventures LLC. (1st spanish versión).
- Tucker, C.S., 2000. Off-flavor problems in aquaculture. Reviews in Fisheries Science 8, 45-88.
- van Rijn, J., 1996. The potential for integrated biological treatment systems in recirculating fish culture- A review. Aquaculture 139, 181-201.
- van Rijn, J., Tal, Y. and Schreier, H.J., 2006. Denitrification in recirculating systems: theory and applications. Aquacultural Engineering 34, 364-376.
- Waterland, 2011. Aquaculture [online] Available at: <http://www.waterland.net/index.cfm/site/NIEUW%20Water%20in%20the%20Netherlands/pageid/15A550B8-FD09-931B-FE544C1F46164A9E/index.cfm#>[Accessed at 10 May 2011]

- Zhu, S., Chen, S., 1999. An experimental study on nitrification biofilm performances using a series reactor system. Aquacultural Engineering 20, 245- 259.
- Zhu, S., Chen, S., 2001. Effects of organic carbon on nitrification rate in fixed film biofilters. Aquacultural Engineering 25, 1-11.

Figure captions

Figure 1: Differentiation of the companies, by nationality (showed in %), participating in the present study.

Figure 2: Companies differentiated by the cultures specie (*)

Notes: (*) The number of companies is not equivalent to the number of species, because some farms are culturing more than one species. (**) As tilapia are considered as two different genera: Oreochronis niloticus and Oreochronis mossambicus.

Figure 3: RAS systems presented in terms of cultured life stages and current operational status

Figure 4: RAS system components – percentage of appearance within the companies

Figure 5: most difficult device to manage within a RAS system according to researchers and consultants

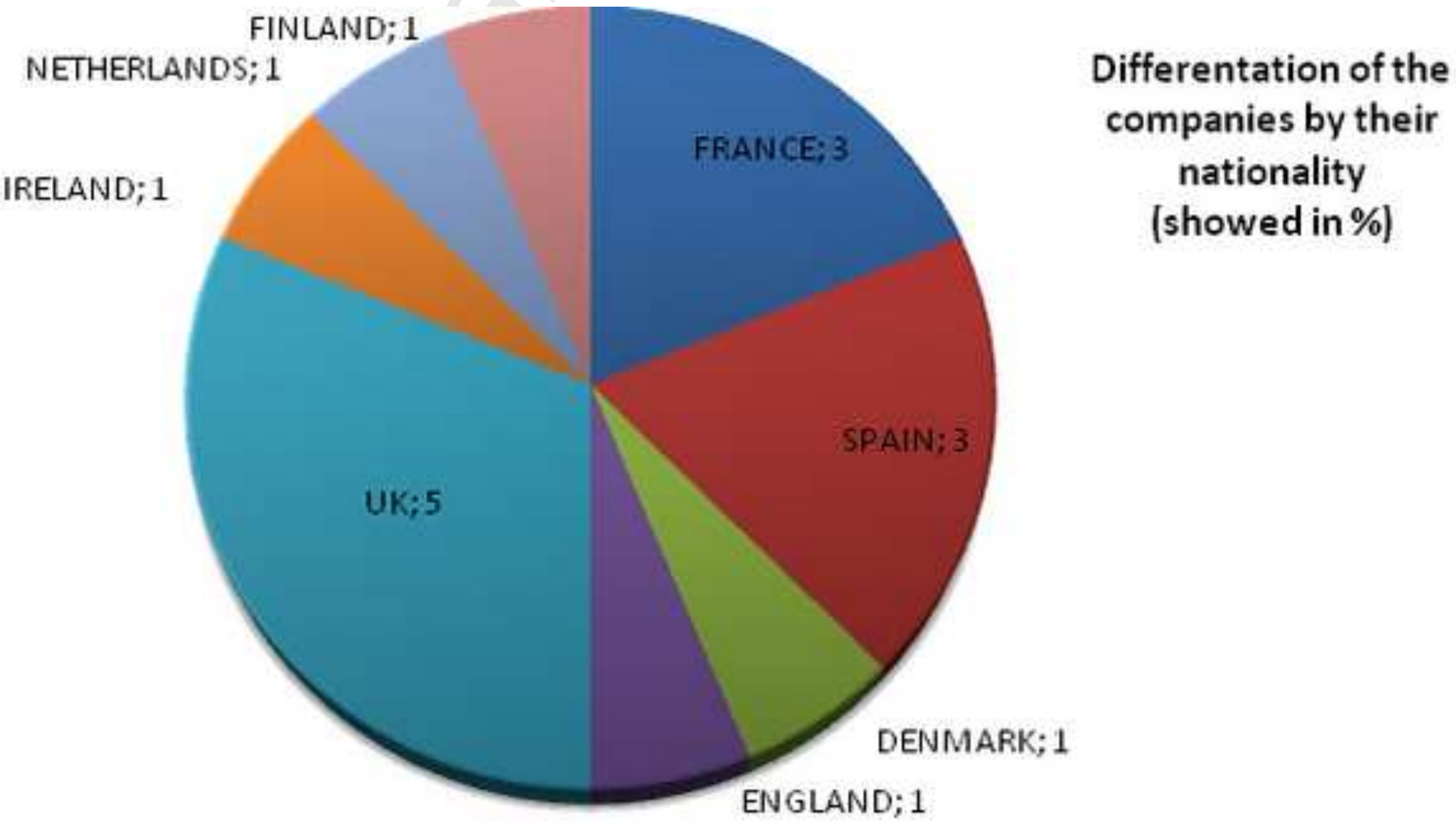
Figure 6: Information needs and research areas currently identified as crucial (results from the on-line survey with the production companies, when asked about the lack of technical information on RAS to be developed)

Note: numbers appearing in the figure represent the frequency that the particular area has been reported by the companies.

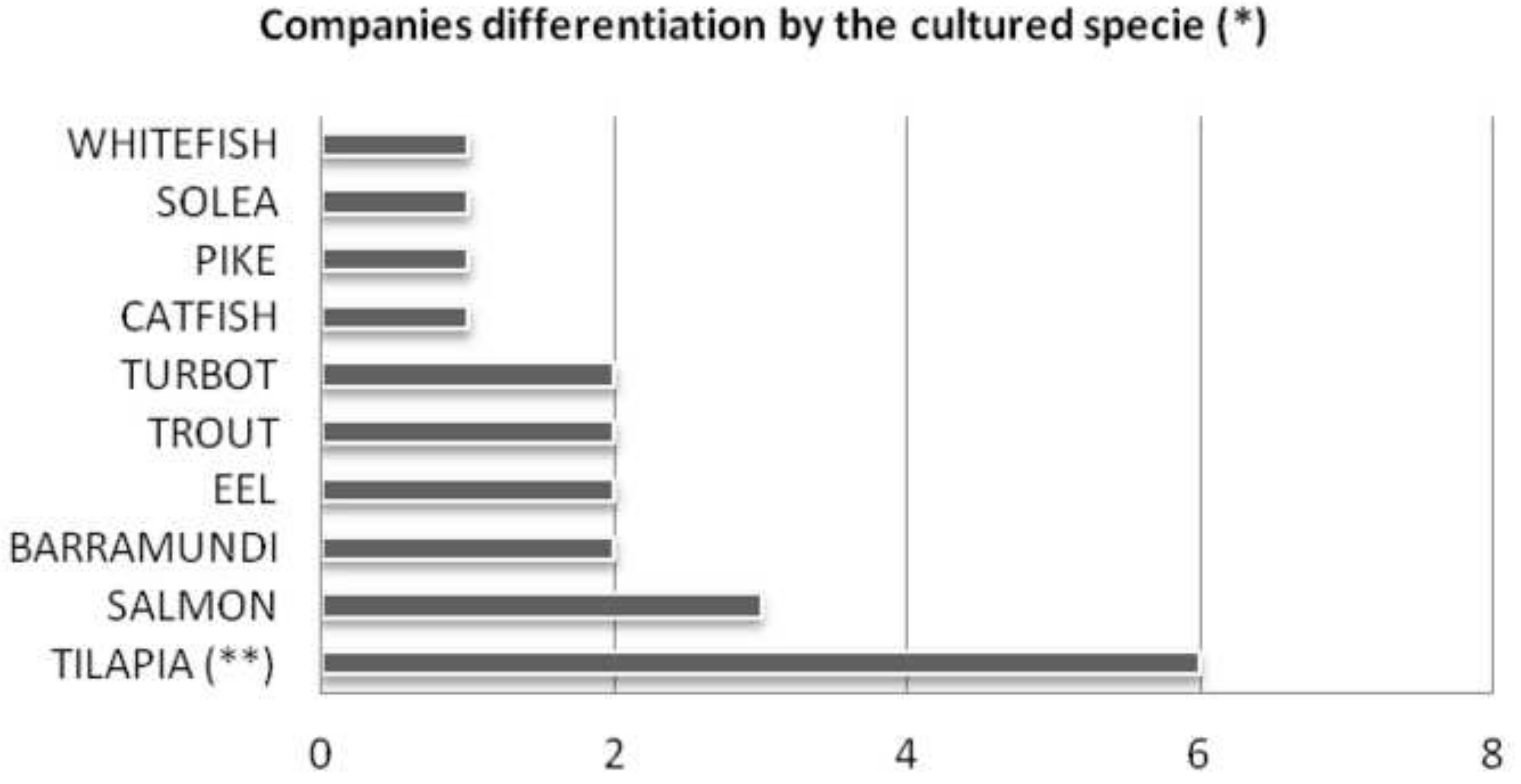
Figure 7: number of years for the return of the 1st investment

Figure 8: Mind map representing factors and interactions, from the RAS designing stage through the product quality, affecting both the production success and the economic profitability of the selected business concept.

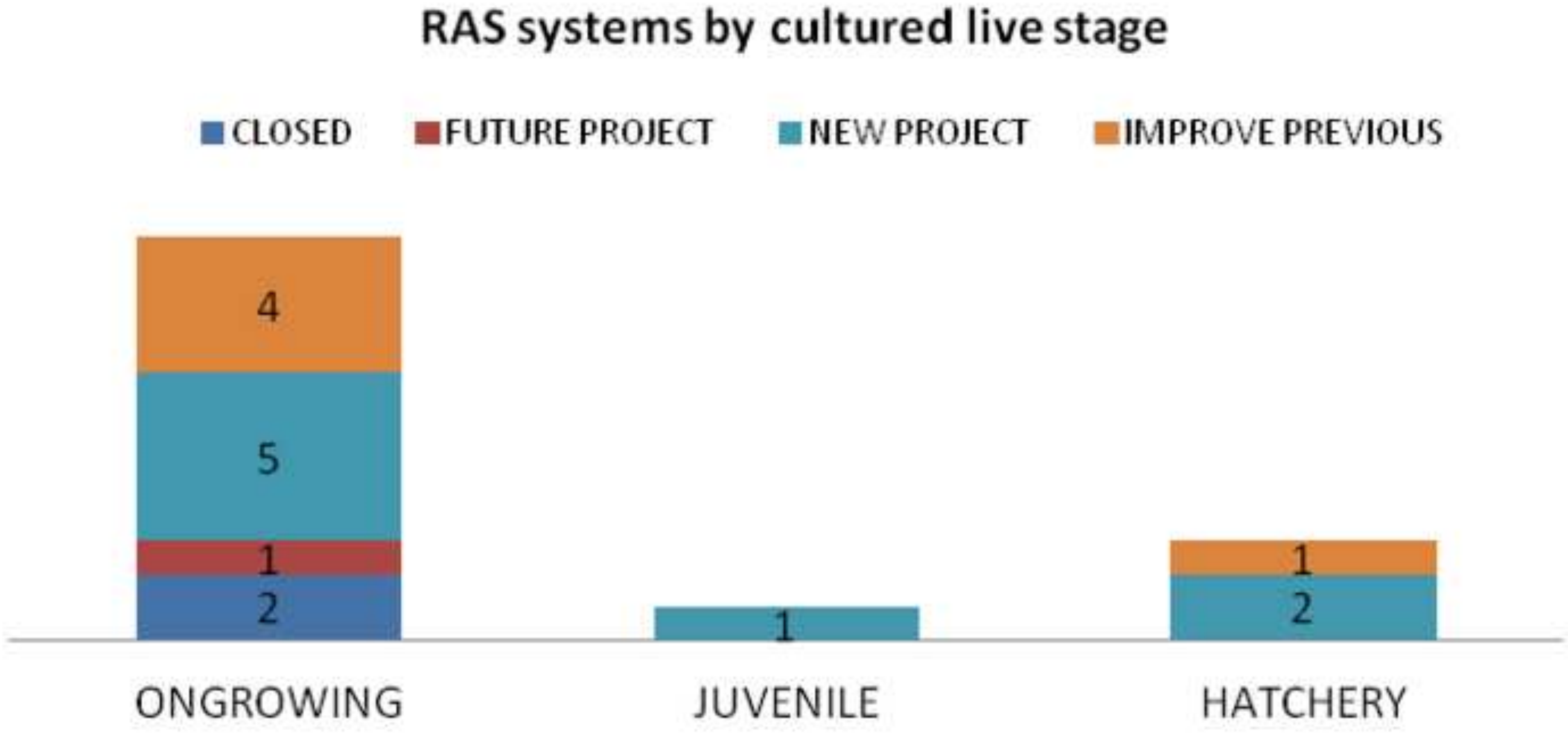
Figure(s) 1 revised

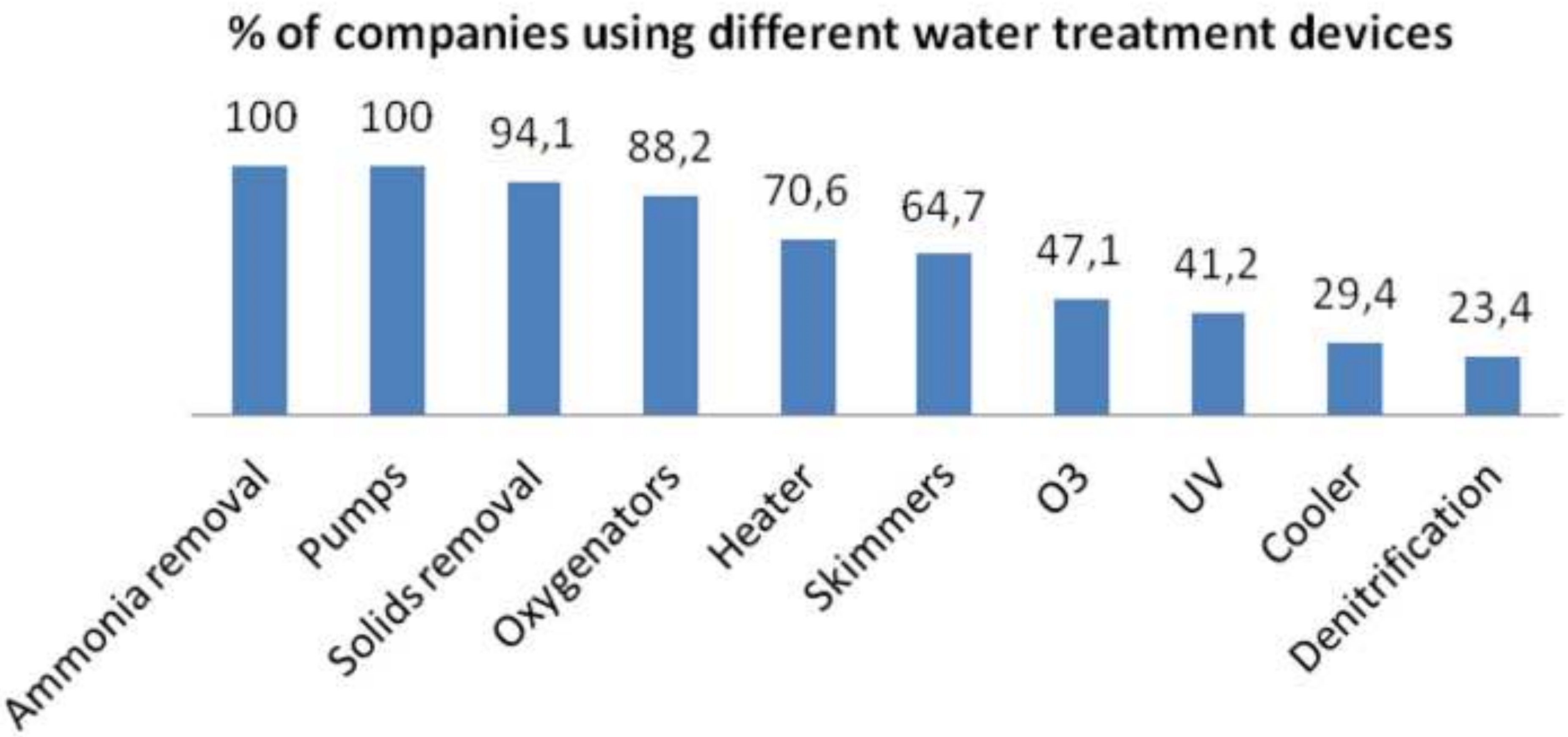


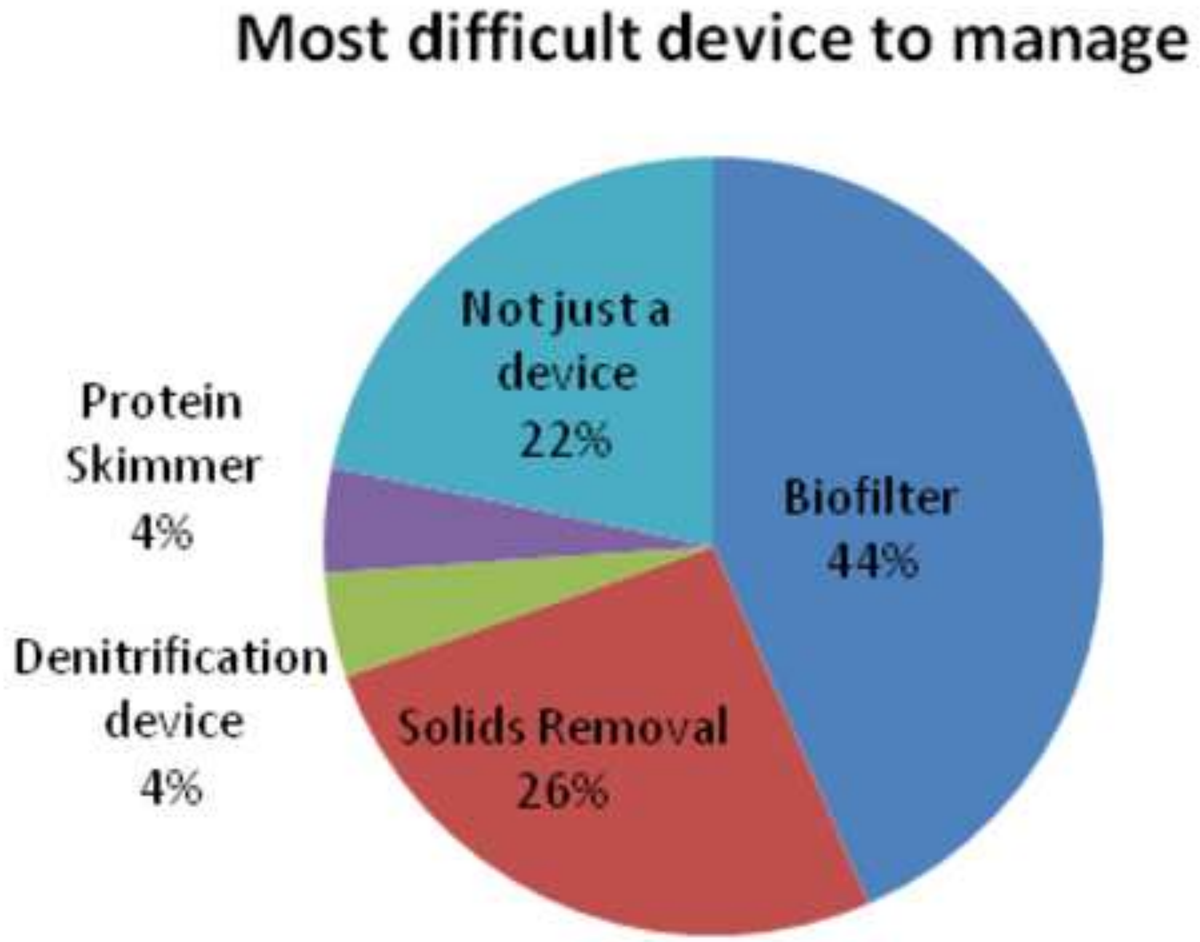
Figure(s) 2 revised



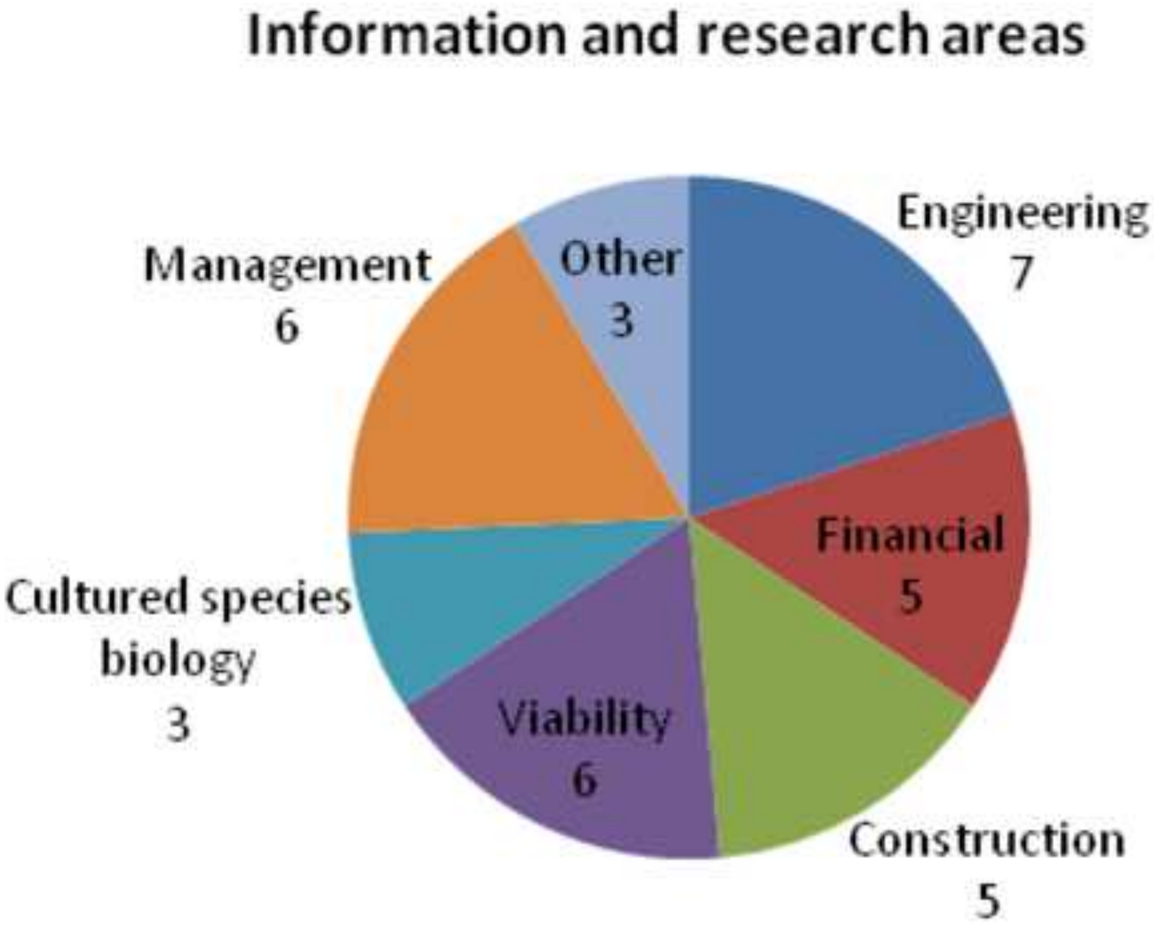
Figure(s) 3 revised



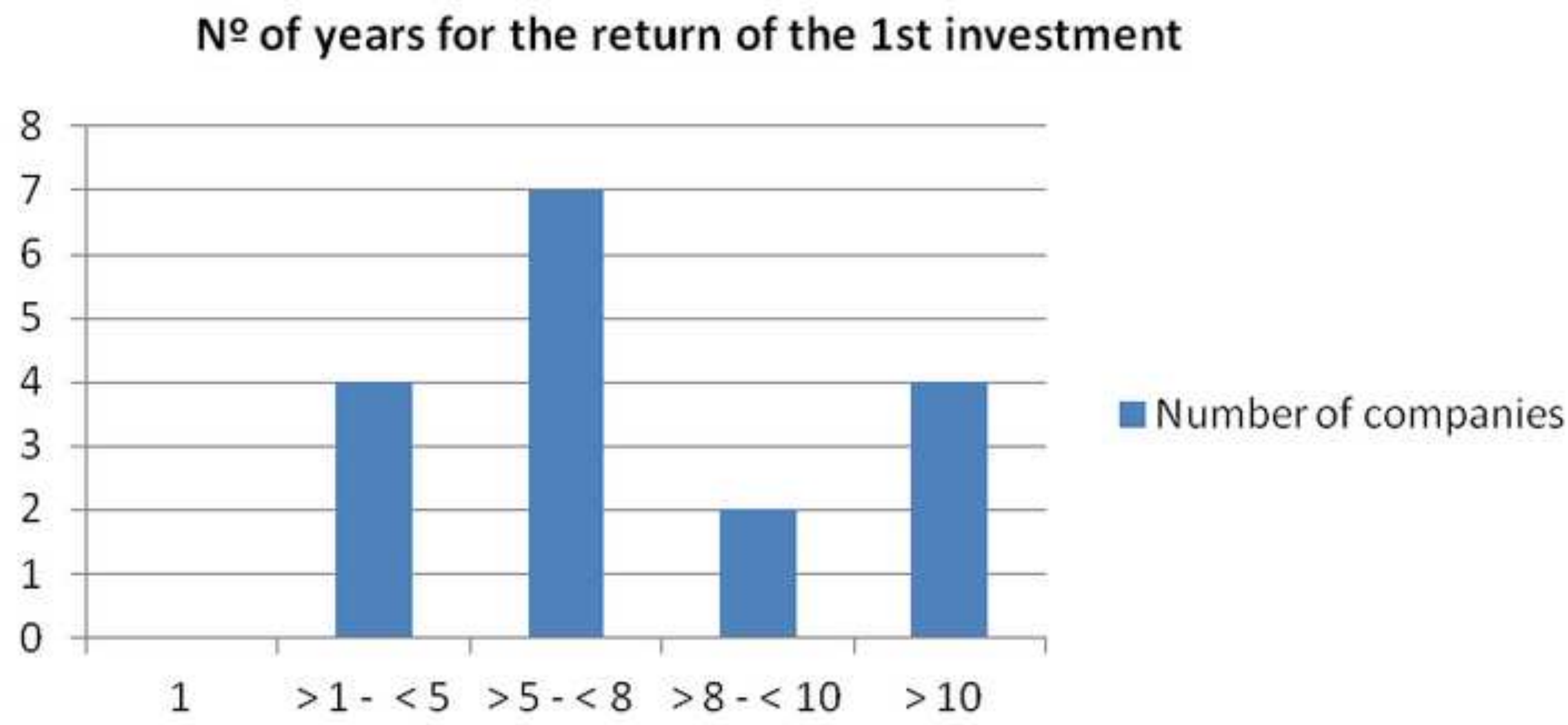

% of companies using different water treatment devices
100
100
94,1
88,2
70,6
64,7
47,1
41,2
29,4
23,4
Ammonia removal
Pumps
Solids removal
Oxygenators
Heater
Skimmers
O3
UV
Cooler
Denitrification

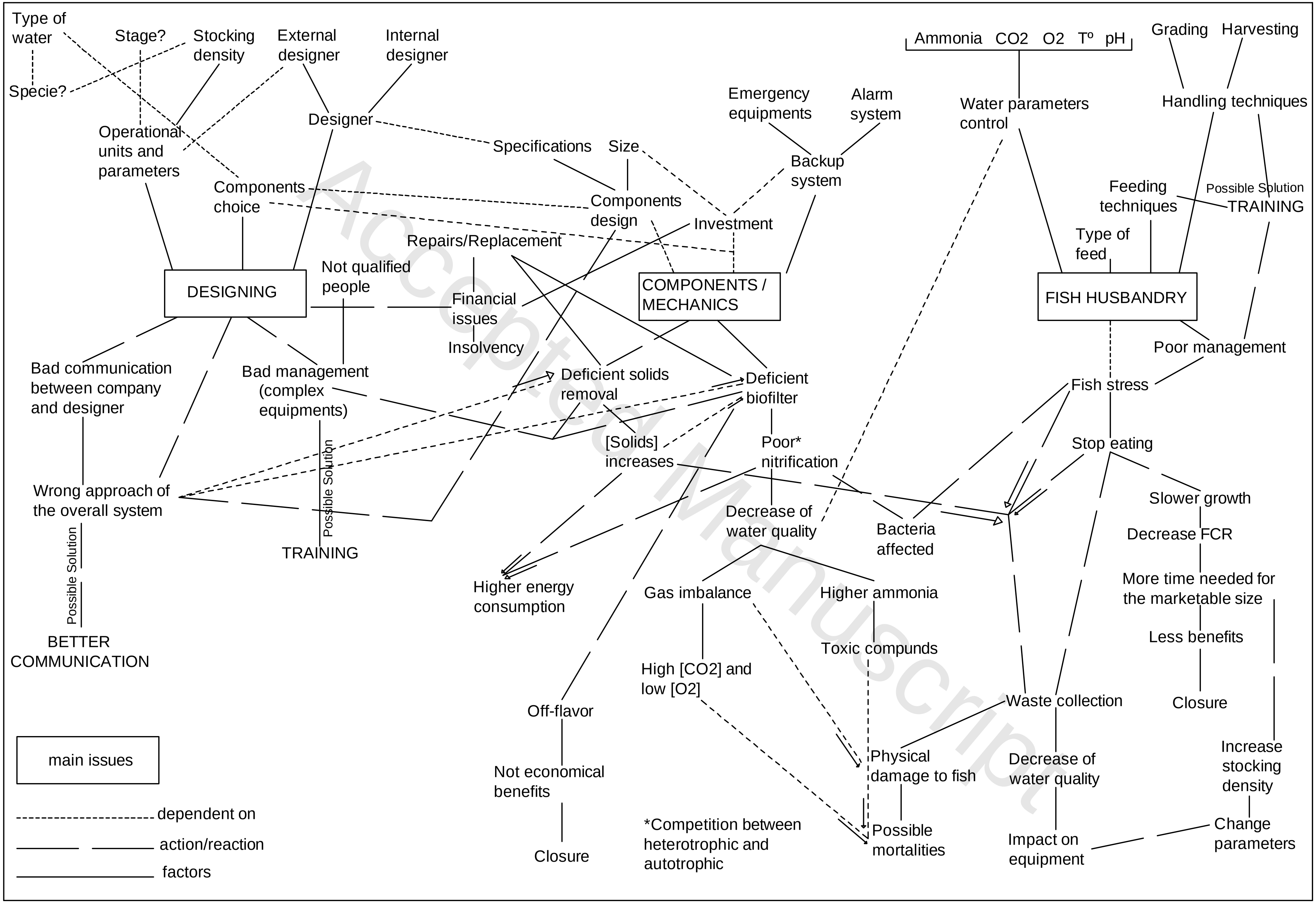

Most difficult device to manage
Not just a device 22%
Protein Skimmer 4%
Biofilter 44%
Denitrification device 4%
Solids Removal 26%

Figure(s) 6 revised



Figure(s) 7 revised




Type of water
Specie?
Stage?
Stocking density
External designer
Internal designer
Designer
Operational units and parameters
Components choice
Specifications
Size
Components design
Emergency equipments
Alarm system
Backup system
Investment
Repairs/Replacement
Not qualified people
Financial issues
Insolvency
DESIGNING
COMPONENTS / MECHANICS
Ammonia CO2 O2 Tº pH
Water parameters control
Grading
Harvesting
Handling techniques
Feeding techniques
Possible Solution
TRAINING
Type of feed
FISH HUSBANDRY
Poor management
Fish stress
Stop eating
Slower growth
Decrease FCR
More time needed for the marketable size
Less benefits
Closure
Increase stocking density
Change parameters
Bad communication between company and designer
Bad management (complex equipments)
Deficient solids removal
Deficient biofilter
[Solids] increases
Poor* nitrification
Wrong approach of the overall system
Possible Solution
TRAINING
Possible Solution
BETTER COMMUNICATION
Decrease of water quality
Bacteria affected
Higher energy consumption
Gas imbalance
Higher ammonia
Toxic compunds
High [CO2] and low [O2]
Off-flavor
Not economical benefits
Closure
Waste collection
Decrease of water quality
Impact on equipment
Physical damage to fish
Possible mortalities
*Competition between heterotrophic and autotrophic
main issues
dependent on
action/reaction
factors

Maddi Badiola-Amillategui is MEng in Agronomy (Univ. Lleida, Spain) and MSc in Aquaculture Systems by the University of Stirling (UK). She was awarded with the best student record of her promotion, which helped her get a scholarship for her doctoral studies. She is currently doing her PhD at the Marine Research Division of AZTI-Tecnalia, studying the technological feasibility of RAS systems for the production of marine species (cod and salmon) in the Basque Country.

John Bostock (BSc, MSc) is Senior Consultant and Manager of Stirling Aquaculture, the consultancy and project management arm of the Institute of Aquaculture at the University of Stirling. He has an active interest in aquaculture system design and optimisation, and is a lecturer to MSc classes in aquaculture systems engineering and business management."

Dr. Diego Mendiola (BSc, MSc, PhD) is Senior Research Scientist at the Marine Technology Department of AZTI-Tecnalia. He has broad experience into research on fish physiology, bioenergetics and husbandry strategies with special emphasis in the development of new production technologies for marine aquaculture. He is currently focused in the aquaculture engineering and economics fields of RDTi. He belongs to the Scientific Board of JACUMAR (Spanish Ministry). He belongs to the Board of Directors of the European Aquaculture Society (EAS) since 2010. Has lead or leads, as project manager, several European Fisheries Funds (FEP) funded projects. Current Supervisor of two doctoral thesis linked to the University of the Basque Country (Campus of Excellence).

Figure(s)

Table 1: Classification of number of respondents to questionnaire

	Contacted	Answer/replies	%of respondents
Production companies	36	16+1(*)	46
Suppliers/consultants (**)	90	18	20
Researchers (***)	50	12	24

Notes:
(*) 16 out of 17 producers are from Europe Thus, to undertake a more objective discussion, the last will not be taken into account, for the quantitative analysis of this project. However, it will be used for qualitative data.
(**) Consultants and suppliers are considered to be in the same area as, in most of cases, suppliers also undertake consultancy work.
(***) For the purpose of this project, researchers are considered as individuals working in a university, in R+D areas in different countries and those who have a background publishing research papers in aquaculture.

Table 2: Design Source of Production Company's System and Indications of Satisfaction

System designed by:		Separate company	Themselves	With some assistance
Nº of companies		10	5	1
%		58.8	29.4	6.9
Mechanical issues experienced	Yes	7	2	1
	No	3	3	0
Good after sales assistance	Yes	6	-	1
	No	4	-	0