DesignACT

Deliverable 1: Inventory of infrastructure and knowledge gaps in aquaculture technology

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Preface

The inventory is the first deliverable of the 6th Framework Programme Design Study DesignACT, as specified in Annex 1 of the contract nr. 0011978. The results were based on an inquiry performed by the project consortium, in collaboration with the PMG and IAG. The outcome of the inventory will be used to identify a priority list of facilities, installations, instruments and services to be included in the new European Aquaculture Centre of Technology.

Summary

A design study, being funded under the 6th FP of the European Commission, is planning the features of the new infrastructure. The research facilities to be provided by the Centre are to be based on the information and views gained through an international investigation involving the many aquaculture stakeholders. This inventory aims to identify the most dominant challenges that are experienced in sea-based aquaculture today and that are expected to become important in the future, as well as the major knowledge gaps are identified. These are related to the aquaculture production itself, to personnel issues and to environmental impact. First, a study was done of existing literature on challenges and trends in sea based aquaculture linked to technological development. Secondly, a questionnaire was spread among European aquaculture stakeholders. The responses obtained from the inquiry revealed a major need for technological development and process innovation to meet experienced and anticipated challenges in intensive mariculture. The results also indicate the presence of a critical mass for the use of and collaboration with the future research infrastructure. The inventory of existing European mariculture research infrastructures has been created to avoid duplication and to identify potential collaborators.

1. Introduction

Aquaculture's potential

The global human population is growing steadily and is expected to reach 10-12 billion people by 2050 (63). Combined with a growing per capita consumption of fishery products, this reveals a trend towards an ever-growing demand for seafood (67). At the same time, some 75% of global fish stocks are depleted in some way. Therefore, aquaculture has a tremendous development potential. From 1980 up to 2000, the industry evolved from producing about 3 mill. tonnes of fish and shellfish to 36 mill. tonnes globally, making aquaculture probably the world's fastest growing form of food production (56). Mariculture in particular developed rapidly after the stagnation of the landings from marine fisheries in the early 1990's (63). The increase in production is also significant in Europe, where coastal aquaculture is dominated by Atlantic salmon, gilthead sea bream and European sea bass. Once problems with larval cultivation and cage culture are overcome, other high value species such as halibut, sole and turbot have a large growing potential.

Innovation

In many ways, aquaculture is still in its infancy and innovation is needed to further develop the industry. The European Aquaculture Strategy pointed out the importance of technological innovation for quality, health and welfare. One of the main challenges identified in the Commission strategy was the development of new equipment and management tools to reduce environment pollution. Other priorities were the development of innovative methods and production systems to support aquaculture diversification and the improvement of technologies for offshore cages (64). Innovations resulting in reaching economies of scale, promoting new productions and creating new opportunities for employment are also encouraged by the European Commission (9).

The policy priorities set out by the Financial Instrument for Fisheries Guidance (FIFG) of the European Union include a decrease of environmental impacts, the development of offshore farms, and a stimulation of internal technology development leading to increased competitiveness (51). As the competition for seafood production is at a world level, Europe should be cooperating and not competing in this worldwide challenge (65).

Environmental impact

Aquaculture has developed during the past decennia from being an extensive activity to becoming a highly intensive industry. This intensification has led to production levels that may in some cases exceed the carrying capacity of the environment (1). Growing awareness of the impacts on nature from human activities combined with arguments such as aquaculture being an environmental and health hazard certainly have given the fish farming industry a bad reputation (19).

However, the environmental impact should also be seen in relation to the economical and cultural aspects. Not only the amount of pollution incurred is relevant, but also whether or not such pollution is in proportion to the greater good and whether or not the situation will improve in time (7). As technology improves, it is expected that the detrimental effects of sea cage farming currently experienced will be further reduced.

Pollution caused by sea cage farming is mostly related to direct waste from fish farms such as uneaten food, faeces and dead fish, chemical leakage in the form of medicines or antifouling components, transmission of diseases and genetic pollution. These events may affect energy and nutrient fluxes, pelagic and benthic biomass and community structure, fish stocks sedimentation rates and may cause oxygen depletion and shifts in algal community (74). The environment is not only affected by the direct input of organic material or chemicals into the marine environment. The production, use and eventual discarding of cage materials and related equipment may also contribute to a pollution of the environment. A life cycle analysis is therefore important to include when assessing the environmental performance of different production systems (16). Material choice is highly relevant in this context, where also the costs of producing the materials need to be taken into consideration (33).

Modern aquaculture is at an early stage of development and new technologies offer great possibilities for achieving an environmentally sound and ecologically sustainable industry through reducing the negative environmental impacts of its operations (19, 56, 58). It is important that these technology innovations receive full support from the industry and are market driven (16).

The situation has already improved largely during the last years. A sharp decline of nitrogen loading of the water due to improved feed conversion ratio, a dramatic reduction in the use of antibiotics due to the development of efficient vaccines and the development of non-polluting production through integrated farming techniques have all contributed to a more sustainable production (56).

A system for labelling environmental-approved farms would not only be an important step towards a reduction in the aquaculture impact on the marine environment. It could also lead to higher value products and have a positive effect on the public opinion (68).

Research needs

The Aquainnovation inquiry carried out by FEAP revealed that technical issues are of major interest especially for large trout and cod farmers. The areas of highest priority for innovative measures were production bottlenecks, integrated aquaculture systems and cage technology (9). A study made by the Norwegian Research Council identified the major technology research challenges in the future as being automation and process control, instrumentation, robotics, advanced IT applications, open sea cages, cage technology and constructions, anchoring systems, dynamic positioning, feeding systems, cages reducing the risk for escapes, use of materials and nanotechnology, alternatives to use of chemicals (anti-fouling), water treatment and recirculation (58). In many cases, marine aquaculture may be promoted by implementing technological solutions used in other maritime sectors, and by applying technological knowledge from other fields such as information, communication and material technology.

This report focuses on the main challenges in sea-cage culture encountered by the European stakeholders and on how these can be met by technological developments and innovation. The aquaculture grow-out period is the phase where most value is added, representing 80% of the assets, 80% of the risk and 80% of attention related to environmental impact (54). The European Commission demands a particular attention to the development of innovative production systems in marine aquaculture resulting in reduced environmental impacts and conflicts of space, in reaching economies of scale, promoting new productions and creating new opportunities for employment.

According to the results from an inquiry performed under the PROFET project, the principal reason for aquaculture stakeholders to participate in research projects was the achievement of technological improvement (23). Technology development may stimulate the aquaculture industry to increase its involvement in research and innovation in collaboration with R&D institutions and the authorities. By joining efforts, different categories of competence know-how and expertise are combined, which is a condition for the realisation of a knowledge-based aquaculture production. A more efficient communication of needs, possibilities and experiences between the stakeholder groups is also a prerequisite for success. In the study carried out by CSN – INTRAN, the sea bass and sea bream sector itself expressed an urgent need to influence future research (9). On the whole, research needs to become more user and industry driven. It has to focus on research fields that are of commercial importance and that can stimulate implementation of research results (58).

DesignACT

The new European Aquaculture Centre of Technology to be established aims to promote research on new technologies and engineering solutions by offering large-scale, experimental facilities. Many European aquaculture nations are confronted with similar challenges, which are independent of the species concerned, such as traceability, escaping and fouling. Some of the research areas the Centre aims to focus on are interactions between technology and biology, automatic control of flexible structures, instrumentation, modes of best practice, environment-friendly technology, product design, personnel safety, verification of physical modelling methods and material technology. Besides the need for aquaculture engineering innovations, studies (72) have shown that also the implementation of existing knowledge is a major challenge. The new Aquaculture Centre of Technology will contribute to an intensified implementation of existing and new knowledge in the aquaculture production line and to the necessary training of the involved personnel.

2. Material and methods

Many recent studies report about important challenges the aquaculture sector is facing and some are even suggesting how these should be overcome. The review reports build their statements on important research results and are a most valuable resource for the creation of the inventory of knowledge gaps and research needs. Experts in the different fields of relevance to sea cage engineering were asked to contribute to the study by informing about crucial reports and key articles. In this way, 75 international publications were analyzed to give an overview over the general challenges and trends in sea-cage aquaculture. The results of the literature study is given in chapter 3.

Most of these review articles, however, are focusing either on specific topics, such as nutrient loading, animal welfare or offshore farming, or on well-defined geographical areas, such as the challenges in Croatian aquaculture or the sustainability of Scottish salmon farming. With the objective to map the most significant technological challenges in European sea-cage aquaculture, a questionnaire was designed covering areas related to aquaculture production, personnel and environmental impacts. A second part of the questionnaire related to the experienced need for technological development, while the last questions sounded out the conditions the new Aquaculture Centre of Technology would need to fulfil. The questionnaire is attached to the report.

After an internal quality control, the questionnaire was published on the DesignACT web site (www.designact.org). Potential respondents were then invited to participate in the inquiry through e-mail directly by the project coordination team. Direct contact with the national aquaculture producer's organisations from the most important European countries contributed to a strong participation of the industrial actors. The use of international networks such as FISH, MARAQUA, and European Aquaculture Society also added to the spreading of the questionnaire to relevant companies and institutions in the sector. In some countries, such as Spain, Turkey and Portugal, problems were encountered to gather enough answers, probably as many fish producers in those countries feel uncomfortable to relate to the questions in English. Upon the suggestion of CETMAR, the questionnaire was translated into Spanish, distributed locally by e-mail, and collected by fax. The Spanish version is also attached.

After about 3 months of operation, 162 responses were collected from 22 European countries and 2 non-European countries. Figure 1 shows the distribution of submitted questionnaires according to the respondents' country of residence.

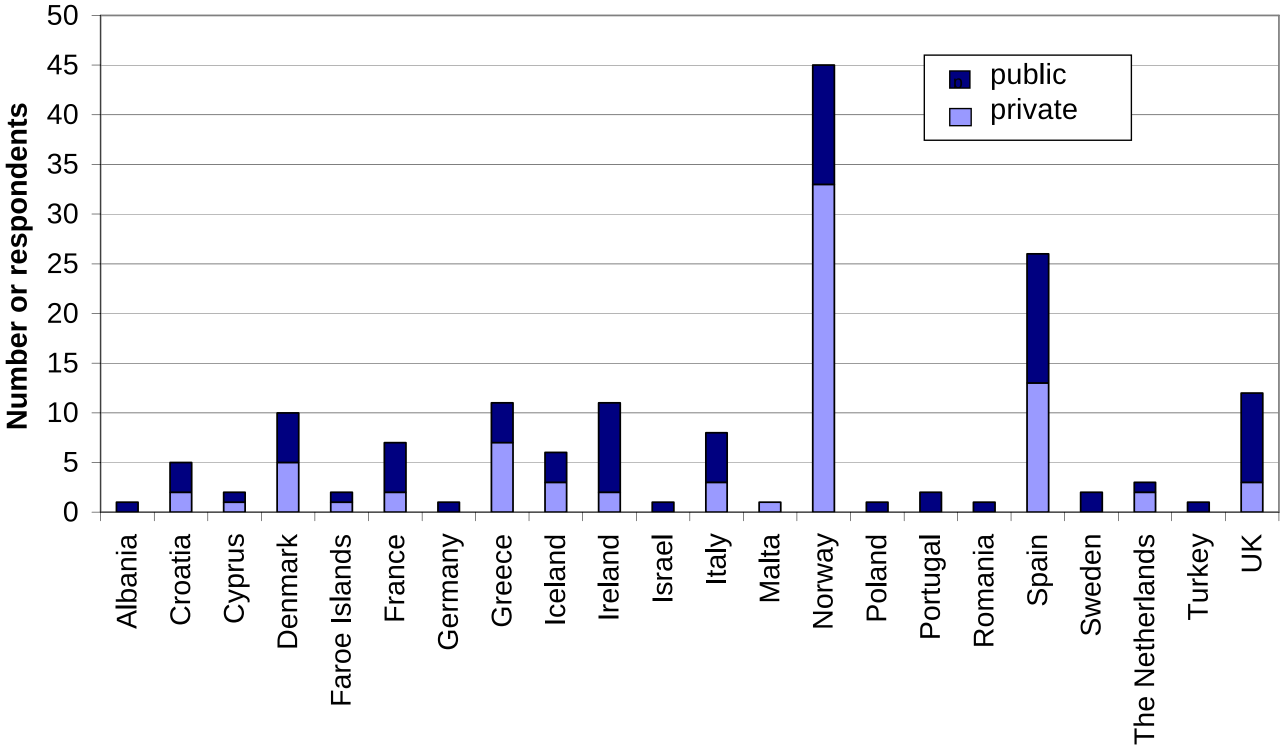


Fig 1: Number of submitted questionnaires according to the respondents' country and type of working place (public or private sector)

Norway and Spain were well represented with respectively 45 and 26 submitted questionnaires, followed by UK (12), Ireland and Greece (both 11) and Denmark (10). As a considerable feedback has been received from the most important seafood producing countries in Europe and from a widespread geographical area, the inquiry is considered to be a sufficient tool for the mapping of aquaculture technology needs in Europe. The private and public sector were almost equally well represented among the respondents, with 49% and 51% of the responses respectively. The countries with the largest aquaculture industry, such as Norway, Greece and Spain have a relatively higher share of private respondents compared to the European countries where less seafood is produced.

Figure 2 looks into more detail to the working place of the respondents, dividing the type of organisation into research centres, authorities, universities, technology suppliers and sea cage farms.

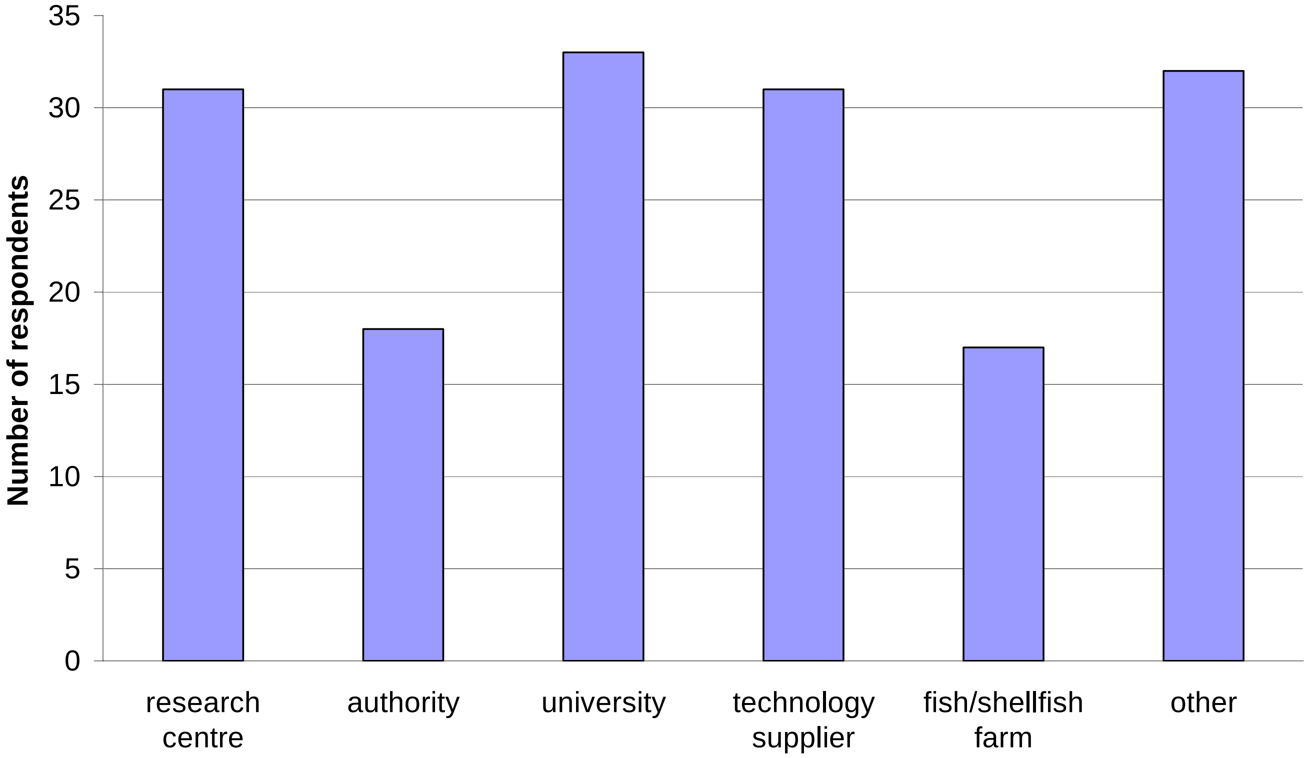


Fig 2: Number of submitted questionnaires according to the respondents' place of activity.

The figure reveals that most respondents from the public sector were working at research centres and universities, while the authorities were less well represented. The technology supplying industry was the main representative of the private sector, followed by the seafood producers. The group representing "others" consisted mainly of private companies such as consultants, producers associations and insurance companies.

The aquaculture sea-cage industry in Europe is taking place in a wide range of natural environments, characterised by a large variety in temperature, salinity, wave height, nutrient load and other important variables that directly influence the seafood production. In Northern Europe, salmonids (salmon and seawater trout) are the main fish produced, followed by cold water marine species like cod and halibut that however still have many obstacles to overcome before a truly commercial production can be reached. The Mediterranean aquaculture production is dominated by sea bream and sea bass, which in this study are both characterised as warm water species. The shellfish industry is spread geographically and represents respondents from Spain, Ireland, Denmark, Sweden and Romania. People working with crustaceans were only found in Ireland and Spain. The technological challenges the industry is facing may in some cases be species-dependent. In order to avoid confusion, the respondents were asked to complete one questionnaire per species group. Figure 3 gives the distribution of input according to the group of species the respondents are working with.

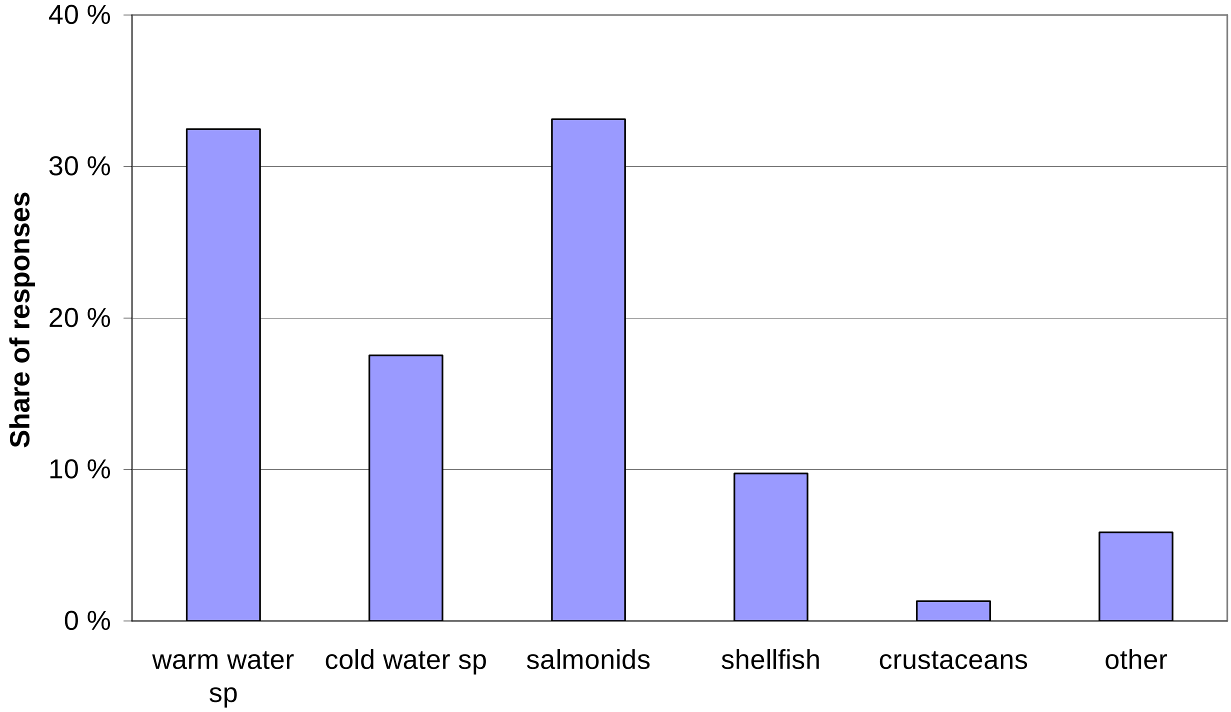


Figure 3: Number of submitted questionnaires according to the respondents' species of interest.

The two species groups that are dominating in the inquiry are also the major cultured species groups in Europe, namely salmonids and warm water species (i.e. sea bass, sea bream, tuna). The salmonids, with 33% of the responses, are represented by the Northern European countries Norway, UK, Denmark, Ireland and the Faroe Islands. The same countries also stand for the input regarding the cold water species (e.g. cod and halibut) (18% of the responses) in addition to Iceland, Sweden, The Netherlands and Spain. The warm water species, representing 32% of the responses, are associated with the Mediterranean countries. A few responses in this category were also received from UK, Denmark, The Netherlands and Germany. Input related to shellfish (10% of the responses) was given by respondents from Spain, Ireland, Norway, Croatia, Sweden and Romania. The challenges experienced in the production of crustaceans are difficult to assess in this inquiry as only two responses were collected in this group. The category "other" mostly referred to respondents working within species-independent aquaculture activities such as equipment supply, training or consultancy.

An analysis of the inquiry results is given in section 4.

3. Results – literature study

3.1. Cost-efficient production

A cost-efficient production resulting in a profitable business is the main objective for any industrial activity. Lower market prices, increased competition and growing labour costs have been important driving forces for making aquaculture production more cost-efficient. Mariculture has evolved from being a traditional, extensive activity to a highly intensive business with efficiencies far higher than the carrying capacity of nature (63).

In general, the prices per kilo of market-size fish have dropped steadily over the past decade. Hence, profit margins are getting smaller and only a continuous increase in efficiency of the production can make the aquaculture industry profitable in the long run.

A more efficient production has been obtained by a larger degree of automation, thereby saving expensive human resources, and by the use of fewer and larger aquaculture producing units. Today, large cages with a circumference of 160 m are already widely used for salmon farming, and it is expected that this gradual increase in size will continue in the future. This is equally true for the sea bass and sea bream industry, which adapted the on-growing technology developed for salmonids culture for the mass growing of sparids (68). However, new challenges are linked to this trend. Large cages require more sophisticated materials and are more difficult to manage. The monitoring and handling processes are getting more difficult, and water exchange may be poorer. Last, but not least, the risks involved with escape also increase with larger production units (2).

There is also a clear evolution towards integrated companies controlling the total production chain from feed production to fish farming and sales (57). As market prices drop for the most dominant cultured species, reduced unit costs of production may be achieved through economies of scale (67). Indeed, larger companies usually enjoy a competitive advantage because they are better able to take advantage of certain internal economies (71).

Diversification may provide a solution to diminishing profit margins. Introduction of new species can contribute to an increased production (19). At the same time, a larger variety of cultured species would make the sector less vulnerable (58). It is therefore expected that the farming of species other than salmon will increase in the coming decade (38).

Aquaculture has evolved from a rather hazardous production at sea to a modern industry, and operations involve increasing technically specialised conditions. Scientific and technical knowledge is to a larger extent than earlier driving competitiveness in the industry (56).
A more user and industry based research will lead to increased resources and more focus on commercially important areas. It may also lead to a faster implementation of the results (58).

The structural changes the industry is undergoing may lead to major logistic and technological challenges, having implications on animal welfare, sustainable production and personnel recruitment. A new operational model where different farm units are grouped in large aquaculture “parks” will require new technology, logistics and service operations (69). This is even more so in offshore farming, where, due to high fixed costs, production must be carried out on a large scale (min 10,000 tonnes per annum) (67). Automation, remote control, energy-efficient operations and transport and simple maintenance are the clues to a successful open-ocean production (62).

The gradual increase in fuel prices may eventually alter the transportation pattern of the world and slow down the globalisation process. This could lead to a reduction in exchange of goods and services between different parts of the world and hence to a more self-sufficient and protectionist aquaculture industry (62). High fuel prices and environmental considerations may also stimulate the application of wave or tidal power in aquaculture production plants (51).

3.2. Animal welfare

Animal welfare is a complex interaction reflecting its physical and mental health and well-being (39). The Norwegian Research Council defines animal welfare as “the individual’s subjective perception of its own mental and physical condition as a consequence of its attempt to control its environment” (59). It is often measured by criteria such as visual appearance, growth rate, incidence of abnormalities and mortalities.

So far, very little consideration has been given to fish welfare when evaluating new technology (59). However, an increased concern for the welfare of fish in general and especially in aquaculture can be noticed in recent years. Fish welfare has received national and international focus from consumers, animal protection organisations, authorities, researchers and the industry. This awareness has been to a large extent based on scientific research indicating that fish have the potential capability for pain perception (3). Other studies report on farming conditions that are detrimental to health and welfare (20).

However, fish welfare is not only linked to subjective observations from consumers or animal protectionists. The industry is also increasingly aware of its importance. The long term effects of bad welfare and chronic stress can lead to suppression of behaviour, immune functions, growth and reproduction, which all influence production and fish quality negatively. A sound management practice, on the other hand, that stimulates animal welfare and reduces stress, may be an important factor in disease prevention. In total, enhanced animal welfare is likely to obtain a competitive advantage by realising growing market opportunities for food produced in animal welfare friendly systems (39).

Intensification of the production at sea has led to an increasing number of deformities and other welfare related problems (59) that are unacceptable. Therefore, there is a significant demand for the development and implementation of welfare technology. New net concepts, for instance, that secure optimal water flow and oxygen supply may lead to increased growth in salmon.

Bad environmental conditions can lead to a reduced growth and a number of physiological changes. The welfare of an aquaculture organism is affected by its physical, chemical and biological environment, nutrition, social interactions, handling and transport and by harmful organisms (59). A combination of several negative environmental factors aggravates the situation. For salmon, sufficient space and water circulation are important to guarantee a good fish health (5). Other species, such as sea bass and sea bream, may have other environmental requirements. The optimal stocking densities, for example, will be dependent on the animal’s behavioural and physiological needs, the environmental conditions, the availability of oxygen and the removal rate of wastes (11,39).

It is therefore necessary to identify for each species, the indicators of positive and negative emotions and the environmental factors that lead to the well-being of animals. The development of registration systems for pain and of measures to reduce pain are also important issues.

The use of monitoring and scoring systems that integrate different parameters and of auditing programs may assess how well a particular producer is doing when it comes to animal welfare (39). Animal welfare can be enhanced by following good management practices. International codes of welfare are standards designed to ensure that the needs of the farmed animals are met.

The European Convention for the Protection of Animals kept for Farming Purposes from 1976 set out a number of welfare requirements, while EU standards such as Freedom Food are dedicated to improve farm animal welfare at all stages in the food chain.

Traditionally, welfare conditions have been documented by monitoring external factors, being mainly stocking density and water quality. However, new techniques, such as the recording of ventilation patterns in fish (24), may open new possibilities for the development of better welfare indicators.

Reduced stress levels in aquaculture may be obtained through new equipment design, management procedures, fish health regimes, avoidance of stress and exclusion of predators. Regular inspection must ensure that significant behavioural and physical changes are detected, while handling should be kept to a minimum in order to avoid distress and injury (39). Artificial light in cages at night may also have an effect on the fish.

Technological development and innovation will undoubtedly be an important factor in the improvement of animal welfare in the years to come.

3.3. Ethical production

Aquaculture ethics refer to the rules or standards governing the conduct of the employees working in the aquaculture sector, relating to the moral choices they make. The moral judgement of the way animals are produced depends largely on personal attitudes, such as the emotions one feels for the species concerned. These attitudes reflect the people's values, which again are dependent upon time, culture, age, stage of life and experience (49).

It is expected that the EU market for seafood will develop towards greater emphasis on ethical sustainability (58, 62), The scientific community should therefore look for logical arguments, supported by facts, to discuss ethics. These may include the number of animals harmed or affected, the cost to each individual and the harm caused to animals in relation to the benefit to man (49).

The production of food in an ethical way has become a clear demand from the consumer's point of view. Fish and seafood production at cost of the marine environment or of animal welfare is no longer accepted by the society as the market is increasingly driven by quality. The animal production itself as well as slaughtering processes have received special attention when it comes to ethics (69). The industry's environmental and social responsibility will therefore be of increasing relevance to the commercial viability of the sector. Commitment to long-term environmental, economic and social sustainability will become a commercial necessity (1). There is a growing need for ecolabelling of aquatic products, as products grown in a responsible manner without harm to the environment are gaining a competitive edge (22).

The development of different types of advanced technology may play an important role in the process towards an ethically sustainable mariculture industry (62, 22):

- large safe and escape-proof fish farm installations
- energy-efficient solutions to transport live fish
- floating storage tanks for slaughterhouses
- fish monitoring and communication tools to optimise the production
- sensors detecting disease outbreaks at an early stage and systems for contamination control
- use of wastes from integrated farms to generate bio-energy

3.4. Water quality

Water quality is a crucial factor when selecting a suitable site for cage aquaculture. In most European states, licence accreditations are directly linked to the water quality at that site.

Water quality parameters may be good indicators of fish welfare. Oxygen levels must be sufficient to satisfy the fish's physiological needs, which are dependent on the species concerned.

Most of the new candidate aquaculture species in the Mediterranean are less eurythermic and euryhaline than sea bass and sea bream and therefore need more stable and better quality of water. Hence, these species need to be adapted to in-sea cage rather than on-land tank technology for on-growing (13).

Technology can be used to monitor and to improve the water quality, as well as to avoid or limit exposure of the produced species to water of bad quality. A new monitoring technology has, for example, been developed under the project Feedtag (24). Here, small electronic "smart tags" provide a continuous recording of ventilation frequency and amplitude in free-swimming fish, which are known to be good indicators of water quality and stress level in fish.

When it comes to avoiding bad water conditions, appropriate actions may be taken in response to environmental monitoring systems which can predict changes in the water column (58). Operation systems can then be developed that respond to environmental changes. Immersed cages may sink to the aphotic zone when critical densities of harmful algae are registered, leading to improved water quality for the fish and hence to better welfare conditions. Benefits of moving offshore: less extreme and more stable water temperature regimes and salinity (67).

3.5. Food quality

The consumption of seafood is steadily increasing relative to beef, chicken and pork. Nutritional benefits have been the driving factor for this trend. However, aquaculture products are also suffering as PCBs, dioxins, mercury and other dangerous compounds are being concentrated through the food chain into the market product (70). In the sea bass and sea bream industry, product quality control and safety have been identified as on of the main current challenges (68). Increased product quality demands from the consumers may stimulate the entire food producing sector to develop a code of conduct and practices and to implement safety and quality standards (69, 22).

In order to offer food safety guarantees, quality management should be improved along the production chain, where traceability and quality are to become an integrated part of the aquaculture activities (58). The promotion and use of electronic traceability systems and the development of internationally recognized requirements for assuring food safety are crucial to reach that goal (26). Operation plans according to the international Hazard Analysis / Critical Control Point (HACCP) standards have been implemented in a number of countries as well as by individual producers (71).

The benefits of moving offshore may lead to the production of a healthier, faster-growing and higher quality fish (67). Indeed, scientific evidence shows that offshore conditions are conductive to the production of healthier, faster-growing and better quality fish with lower mortality rates.

3.6. Fouling

Fouling is a well-known problem in sea cage farming. The process of fouling starts within minutes of immersion in the water, first with the formation of a biofilm and finally as a colonisation of the surface with seaweeds and invertebrates. Problem areas include immersed structures (such as cages, netting and pontoons) and farmed species, particularly shellfish. Antifouling strategies being used today are mechanical cleaning, which is labour intensive and tedious, and biocidal coating, which needs to be repeated each season. Both imply high costs, and the latter is an important source of pollution (mostly Cu_2O). With application of Biocides Directive EC98/8/EC (17) the choice and availability of biocides as antifoulants will become much more restrictive.

Biofouling greatly reduces the efficiency of materials and equipment: it damages equipment and flow can be significantly reduced (preventing oxygen and waste product exchange). Biofouling organisms can compete for recourses with cultured organisms and can include predators, harbour diseases or have direct toxic effects. Annual costs to replace nets and reapply antifouling are considerable. Uncontrolled biofouling leads to increased maintenance costs and production losses (lower growth and poorer quality). Potential cost savings are estimated to be 5-10% of the market value (75). Given the low cost margins, it is vital that low cost, practical and easily applicable methods are found and introduced to control biofouling on sea nets.

In accordance to the new Biocides Directive, the use of anifoulants and the leakage of harmful impregnation chemicals for nets should be reduced to a minimum (26).

Fouling has been regarded as a major production and environmental problem in sea-cage aquaculture for many years. As the traditional methods of physical cleaning and the application of antifouling substances have proven to be both costly and detrimental to the environment, alternative methods are continuously under investigation. Some of the methods that have been used locally or that are under development are biological control through grazers, avoidance, new materials (coatings), new cage designs, alternative antifouling solutions such as acetic acid.

Fouling is a general problem, affecting all structures set out in an aquatic environment. The shipping industry has been forced to deal with fouling for many centuries already, and aquaculture could easily take advantage of the technologies and expertise available in that sector. Antifouling technological solutions that may be considered are vibrations, physical deterrence (air curtain), colour of substratum, magnetic forces, electrical methods generating chlorides or pH shifts, robot cleaning technology, fouling release coatings such as silicone, fluor-silicones or nanotechnology base materials, surfaces with defined micro-structures, hydrogels and removable foils. New non-toxic antifouling coatings and the use of enzyme technology to weaken the bonds between biofouling and stock organisms could also improve the current antifouling management (37).

Open-ocean aquaculture may also contribute to less fouling as the tougher physical environment at exposed locations reduces the ability of sessile organisms to colonise the nets (67).

3.7. Monitoring and control

Traditionally, monitoring of the various elements of sea cage farming, such as fish biomass, health and welfare, water quality and cage performance have been very dependent on visual criteria. Control of these variables is often performed based on the experience of each individual farm operator, and is a practice, although functioning well in many cases, to be avoided.

Current monitoring methods tend to register disease, mortality rate, age, size and growth rate and efficiency, giving a snap-shot of the performance of each production unit (42). However, new technology should be developed to allow registration of the lifetime history of these criteria allowing a more comprehensive picture of the overall situation. A better knowledge of caged fish behaviour through biotelemetry for example may lead to an optimally adapted cage design and feed management (16). Automated measuring instruments and sensor technology are also powerful tools for detecting ecological changes in coastal waters.

Optimal production at an aquaculture site requires an effective information exchange between feeders, sensors, biomass estimators, etc. The application of information technology used in other sectors may generate useful solutions for the sea-cage production.

There is also a need for standardisation to improve information exchange, and for an implementation of standards in the practical operation (40).

Information and computer-based technology from other sectors, made applicable for use in sea cage aquaculture may innovate the way of monitoring and controlling the most important variables, such as feed availability, fish growth and welfare, net fouling, escape and water quality.

3.8. Documentation / traceability

Traceability which can provide a food safety guarantee for consumers has been identified as a growing global demand. The focus on quality life, fish welfare and sustainable production initiated this trend and was accelerated by numerous food scandals in the animal production sector. Documentation needs not only to guarantee a safe and high quality product. It also needs to address a number of fish welfare factors, including the quality of the water environment and the stress levels the fish have been exposed to (24).

The introduction of internationally recognised certification standards for aquaculture farms is an important challenge (56). The application of these standards may certify the quality of the production plants through independent testing and documentation of the farm facilities. It may also contribute to the awareness of consumers towards the sustainability of farmed fish and seafood.

In order to strengthen the consumer's confidence in farmed fish products, traceability and quality need to become an integrated part of any aquaculture production (58). This will require an adaptation of the current training and professional routines in the daily operation (40).

As new animal welfare standards will become implemented internationally, documentation of the fish's living conditions and of a responsible slaughtering process will be required (58).

The introduction of electronic traceability systems in the production chain, and the development of new sensors would contribute to a continuous documentation of the production processes (58). Parallel with technological innovations, traceability would also be promoted through the development of international standards and the improvement of quality management (26).

Traceability should not only be considered as a necessary process to satisfy today's expectations and regulations. It has been shown that a traceable product also has a competitive advantage and an improved cost-quality ratio, and that it has a positive impact on the company's brand (40).

3.9. Handling / Transport

During their life at sea, fish are undergoing handling and / or transport on many occasions. Transfer from hatchery to sea cages, vaccination, grading, change of cage and the ultimate pumping or shuffling from the cages in well boats and further on to the slaughter houses are all handling operations that are part of the regular aquaculture on-growing process. These types of handling are clearly stressful to fish, as observations show that fish do less well if they are handled frequently (3).

Handling and transport of animals are closely related to welfare issues. Avoidance of stress symptoms caused by handling prior to slaughter is also essential for the production of a fish product of the best quality. Responsible handling and harvesting regimes are therefore considered as crucial factors not only for the welfare of the animals but also for the product quality (15). The transport of live fish should be done without delay, with an adequate oxygen supply and without rapid changes in variables such as temperature and water quality, and in containers designed to eliminate injury (39).

International routines need to be established to follow grading and transfer of animals. During this process, the quality of the recorded data needs to be assured (40).

Although damaging for the animals, handling is impossible to avoid in sea-cage farming, and therefore methods and technologies need to be investigated to make the process as harmless as possible. The utilization of gloves in new materials that do not affect the fish skin and the development of systems that protect the animals from sound, light and extreme temperatures should contribute to less destructive handling methods (34).

When evaluating the possibilities for offshore aquaculture, the transport of living fish in exposed ocean areas is an important challenge to be met, especially when taking into consideration the risk of escape and its consequences. Taking into consideration the increasing transport costs over larger distances, it is expected that the size of the well boats will also increase (62).

3.10. Working conditions

The marine aquaculture industry is an important contributor when it comes to the creation of employment in rural areas. However, the working conditions at most sea-based aquaculture plants are far from satisfactory, and the sector still experiences a high number of accidents each year (69).

By reducing the operational risks at the grow out units, the number of accidents and near accidents could be considerably reduced (26). If personnel safety is being taken seriously and the work conditions are improved, a career at an aquaculture plant becomes more attractive, which again may secure personnel recruitment in the future.

Climate models are being increasingly unanimous that extreme weather will become more frequent (41). So even if the current trend towards open-ocean aquaculture would be reversed, operations in the marine environment will become tougher and involve more risks.

Considering the availability of competent personnel, there is a need for educating “aqua-engineers”, who can guarantee the optimal use of equipment and materials at the aquaculture units. Alterations in the aquaculture organisation structure may lead to different working conditions with shift arrangements where the workers are “two weeks on – two weeks off” (62).

Safety linked to work at aquaculture sea cages and vessels may be improved through optimising the infrastructure, such as cages, platforms, feeding stations, vessels, etc, and the operational and security routines. Determined training and education are also important factors to promote safety at work (25).

3.11. *Competence level of the personnel*

A successful commercial aquaculture production relies on the presence of competent professionals performing a range of activities. These daily routines performed at sea-cage installations are often physically demanding and full of risks. The dangerous nature of the jobs combined with their location in rather isolated places may reduce the attractiveness of a job in the aquaculture production, which again may lead to recruitment problems in the sector.

As intensification proceeds, the need for more knowledge-based aquaculture is increasing (14). The education of specialised labourers and of university level profiles is essential to provide the aquaculture sector with the necessary skills and expertise. As technologies and production processes are developing fast, there is a need for continuous training of the employees and for improved career programmes. The staff members in medium size fish farms are also often responsible for a number of diverse activities, demanding a wide range of knowledge and skills. Certified training in a well-defined set of applicable skills may meet the needs for competent and flexible personnel. Improved career programmes will also increase the appeal of the profession and promote employee safety, product quality and profitability (71, 58). The growing internationalisation of the industry makes new demands on staff members, valorising language abilities and mobility at a much larger degree than before. In Eastern and Central Europe, human resources management, including language training, has been identified as a vital component of aquaculture development in the region (22). The continued development and implementation of robotics in aquaculture operations at sea will moreover reduce the need for low-qualified and cheap labour (62).

Good quality equipment often fails to perform satisfactory due to insufficient training and bad maintenance. It is therefore essential to provide training in the operation and maintenance of a technological device when taking into use new aquaculture equipment (14).

Through training programmes, recognition of the role of women in aquaculture enterprises may be promoted. This may be achieved by improving the quality and number of work opportunities for women in aquaculture (50).

3.12. Efficiency of product operations

The aquaculture sector is still very much characterised by manual operations and heavy work. However, the recent evolution towards fewer and larger grow-out production units is very likely to cause an increasing industrialisation of the production activities and rationalisation of the working operations (69).

With low global market prices and high labour costs compared to Europe's most important competitors, the implementation of robotics in aquaculture production processes is becoming increasingly profitable. The development of new automation technology need to take into consideration the biological requirements of the cultures species to avoid that the implementation of robotics would happen at the expense of animal welfare (58).
If technologies for finfish cage farming are to be developed in an economical sustainable way, these should have cross-species applicability. New technology developed for salmon in Norway should for example be directly transferable to Mediterranean waters for use in sea-bass or sea-bream farming (67).

As open-ocean fish farming is becoming attractive, more research and development of offshore cage technology must be promoted. Besides the necessity for a high level technological environment, offshore aquaculture has a special need for qualified manpower, and developed infrastructures (65). The offshore zone is a hostile, high-energy environment. Operations in exposed areas require therefore more robust materials and equipment as the structures and moorings must be capable of tolerating the loads they will be subjected to (67). Access to the offshore farming units is often difficult if not impossible, necessitating production units to be driven autonomously. A large feed storage capacity, self-supplied sun, wave, current or bio-energy and automated production with remote control systems are essential features in off-shore farming (58). Other technologies that may promote the feasibility of operations in exposed areas are advanced positioning and dynamic anchoring systems. Experience from other sectors such as the oil industry may clearly stimulate this process.

Off-shore cages beyond the 200 mile zone are anchored or floating. They are self-supplied with feed and energy through. A number of different species are produced in a pollution-free environment. New material and information technology make the production units autonomous and with remote control via satellite (58).

3.13. Nutrient loads / Eutrophication

Aquaculture production units are adding a considerable amount of carbon to their surrounding environment through the leaking of wasted food pellets or faecal excretions. The carrying capacity of a specific site is dependent on the total concentration of nutrients discharged and on the rate at which it is exposed to suspended organic matter (46, 71). The organic enrichment of the seabed is the most widely encountered environmental impact of aquaculture in sea cages (44).

In contrast to agriculture production or on-land aquaculture, sea cage farms are essentially unable to limit the effects of their operations to their own property (7), and wastes are discharged directly into the open sea without treatment (38). It has been shown that this waste flow may lead to nutrient enrichment in the vicinity of aquaculture activities. This enrichment may affect the biogeochemistry of benthic communities negatively and may cause a change in the natural ecological structure, which again may lead to toxic algal blooms (70, 53). In the Mediterranean, the release of nutrients might damage large macrophytes such as *Posidonia oceanica* through a series of indirect effects (45). Chemical pollution may be caused by the release of therapeutic chemicals (1).

The local impact level of aquaculture depends on the physical and chemical characteristics of the surrounding water masses. Most of the fish farms are likely to be sited in areas of relatively intense water currents and therefore it is unlikely that the water quality in the immediate vicinity of an individual farm would be severely affected. At the large spatial scale the effects are also small in comparison to other sources of nutrient discharge. A study found out that the overall N and P waste from fish farms in the Mediterranean represents less than 5% of the total annual anthropogenic discharge. In the long run, fish farm waste could cause a 1% increase in nutrient concentration in contrast to other anthropogenic activities which might double the Mediterranean nutrient pool (46).

At intermediate scales however, such as a zone for aquaculture development, there is some potential for hypernutrification or even eutrophication, particularly when poor flushing is involved. This might have severe consequences for the fauna and flora in the water column and on the sea bottom. The excess organic material reaching the seafloor can determine the species composition and biomass of benthic communities (74).

If the aquaculture production is to continue its increasing production without any adaptations, it is likely to believe that the water quality will also be affected at a larger scale. However, recent advances in feeding technology, and in particular the introduction of demand feeding systems, have lead to an important reduction in nutrient discharge (68).

The effects of nutrient enrichment are not necessarily negative. Recent data have shown that there might be a positive effect on the local fisheries in oligotrophic environments (28). This may also be exploited by a local recirculation of the nutrients excesses through producing a second crop at the same site (16). An optimisation of integrated aquaculture systems requires more research and technology transfer on mixed plant/animal systems from Asian freshwaters where there is a long tradition for these practices (22).

In case bad environmental conditions would lead to toxic algal blooms in the upper sea level, immersed fish producing units may provide the necessary protection to the fish during critical situations (69).

3.14. Escapees

As the aquaculture industry expands to meet human demand, the farming of marine finfish in open pens continues to increase along the world's coastlines (53). The trend towards larger production units and more exposed locations also contributes to an increased risk level as the consequences of a possible escape are far more serious compared to farms working with small cage units (69). With the expectation of climate conditions to become more extreme, cage damages and hence escape may also occur more frequently.

The impact of escaped fish is perceived on many levels and entails a risk for wild populations (through competition with wild fish and genetic interaction), for the ecosystem (through transmission of pathogens) and for the society (through direct cots, lost capital and public perception problems) (53). It has been suggested that escaped fish do not remain near farms for long (5). The ecological effects are therefore expected to be felt over a rather large geographical area.

Escape has been documented in all aquaculture regions in Europe. In 2000, it was estimated that 0,5 mill. salmon escaped from Scottish farms (1), and as much as 40% of Atlantic salmon caught by fishermen in areas of the North Atlantic Ocean are of farmed origin (53). Escape is also regarded as an extensive problem in the Mediterranean area (6). The loss of farmed animals occurs both through regular, low-level "leakage" and through episodic events such as storms (53). The latter events are likely to increase as climate conditions become more extreme, but the development of stronger cages that are more resistant may hinder an aggravation of the situation.

Its supposed effect on the natural environment makes the issue not only an important challenge for producers but also for authorities. The demand from both stakeholder groups for new technological solutions is expected to increase until the production of cages that are 100% secured against escapes will be a reality (69, 58, 26).

Most of the escapes events are linked to technical failure. In Norway, guidelines to minimise salmon escapees through correct use of equipment and careful handling operations have already been developed and implemented (25). These should be extended to other fish species and strains (19) in order to obtain a complete European action plan.

A number of technological measures have already been adopted to reduce the incidence of escapes. The use of stronger net materials, tauter nets that deter predators from grabbing fish and covers on boat propellers to avoid net tears have proven to be efficient actions against escape (53). The introduction of new construction materials based on nanotechnology may potentially contribute to a further reduction of escape by creating less heavy and stronger fish cages (58).

However, closed containment systems are the only safe solution to avoid escapes (70).

3.15. Direct effect on surrounding wildlife / wild fish

Even if a zero-escape is assumed, sea cage aquaculture production still may have secondary effects on the surrounding fauna. Intensive finfish aquaculture involves the supply of high-quality artificial feeds and unused feed pellets may cause wild fish aggregations in the direct neighbourhood of the cages. The presence of fish farms may hence affect the presence, abundance, residence times and diet of wild fishes in a given area. The wild fishes associated with marine farms consume the organic matter leaving the net-pens and play therefore an important recycling and regulating role towards the benthic community structure (74). However, fish aggregations may also lead to the spreading of parasites from farmed to wild fish.

Wild fishes may have a modifying effect on the amount of fish food that reaches the sea floor by consuming food that falls through the cages. Less fish food will reach the bottom and more faeces will be produced instead, hereby changing the nature of the farm effluent dispersal because faecal material drifts further from the cages than food (12).

Due to the aggregative effect of fish farms and the prohibition to fish within farm areas, coastal sea-cage fish farms may act as small pelagic marine protected areas. Scientific studies have also shown that populations living in areas close to fish farming zones suffer little losses during winter (48). However, a possible negative effect is the alteration of the community composition in surrounding waters as only those species that associate with fish farms increase their production (12). Scientific research shows that in the Mediterranean, the sea bottom close to the rearing cages is dominated by opportunistic organisms, which are indicators of organic contamination.

The environmental impact of marine fish farming is highly correlated to its location (74). By moving the aquaculture production to offshore locations, the levels of ecto-parasitic infestation and the impact on the seabed may be reduced (67).

Environmental monitoring in the vicinity of fish cages will provide documentation of the situation in the neighbourhood of sea cages. This can be achieved by using existing technology in new ways or by developing new technological solutions (69).

3.16. Conflicts of area use

Human populations are increasingly aggregating on the coastlines in the major continents. In addition, dynamic coastal activities such as aquaculture, tourism and waterborne transport are all expanding. These trends inevitably lead a continuously more intense and tougher competition for space (47, 36, 19).

In regions that are largely dependent on income from the tourism industry, it is of utmost importance that mariculture activities are accomplished in a way that inflicts no damage to the environmental assets, such as landscape and water quality (71). If sites are inappropriately located, conflicts with other users, interests and resources are unavoidable (1). A constructive communication between tourism, aquaculture and environmental organisations is therefore to be promoted.

Conflicts of area use, anthropogenic sources of pollution limiting coastal aquaculture production and the shortage of sheltered, deep water inshore sites in most European regions is forcing marine fish farms further away from the coastline into more exposed areas (27). Some even claim that open ocean aquaculture may be the only viable option for future seafood production to meet the desired consumer demand (4). In the Mediterranean, seashore conflicts have already eased mass production in large size open sea cages at low stocking densities. The moving of cages further from the coast and the use of experience from outside the aquaculture sector (such as oil platforms) is in line with a recent European Commission policy statement on aquaculture states (67).

In order to avoid future conflicts of use and to insure an integrated management of the coastal zone, instruments and methods need to be developed (26).

The moving of aquaculture cages to more exposed areas requires more severe demands on technical equipment.

3.17. Aesthetics

The sea landscape is part of the natural assets of coastal regions and any disturbance of the view or the general perception of the sea line is perceived as negative. As the presence of aquaculture plants, including sea cages, sea facilities, vessels and infrastructure on land, contributes to the disturbance of the coastline, it is important that these facilities are designed in an aesthetical way.

Aesthetics is a very subjective issue, for which no objective criteria can be used. Conflicts caused by the marine aquaculture industry in the Mediterranean are mainly linked to the visual and odour impacts of the production (6). Most sea-cages, observed sideways, are far from pretty to look at. Even though the infrastructure is a foreign element in the marine environment, its design does not take this into consideration. Its form has only a functional concern and expresses very little, if any at all, aesthetic reflections. Its colour is mostly grey, having the objective to be as little visible as possible, but expressing an anonymous and dull installation of a very low aesthetical level (33).

When designing new aquaculture units, these have to fulfil a number of necessary functions, such as maintaining the fish inside the cage, keeping the cage buoyant and providing the opportunity to feed, inspect and harvest the animals. In addition, the site also needs to express certain values linked to aquaculture, such as providing a good and safe environment for the fish and for the employees, and avoiding escape and harmful effects on the environment (33). A positive attitude towards sea cage aquaculture may also be achieved by giving more attention to the infrastructure design itself and to integrate it better with the surrounding environment. The objective can be either to hide the production unit as much as possible or on the contrary to make the construction an aesthetic landmark in the coastal landscape. In both cases, forms and colours need to match in order to give the infrastructure a strong identity. A good maintenance of the existing facilities is also crucial to avoid deterioration of the materials and buildings and hence to preserve their aesthetical value.

3.18. Waste management

Wastes from sea cage aquaculture are inserted into the marine environment through leakage of feed pellets, faecal matter, chemicals and dead or escaped fish. The EU Water Framework Directive is today a key operational tool for the protection of the European water masses. It is also of major importance for the way the aquaculture sector is treating its effluents. Through an efficient management, the waste effluent rate and levels may be reduced by a decreasing the amount of wastes produced and by eliminating or diluting the wastes before they enter into the environment.

Through improved feeding technology and methodology an even closer match between feed supply and demand may be obtained, leading to more efficient use of fish feed and less nutrient loss per ton of fish produced. It is therefore expected that nutrient loss will not increase proportionally with further increase in production (46). The choice of appropriate management solutions related to stock densities, feeding regimes and stress prevention as well as the use of continuous monitoring devices may further reduce the effluent discharge from aquaculture (53).

The use of closed containment systems with non-permeable nets would allow the producers to treat aquaculture effluents before entering the marine environment. The technology required for closed containment systems already exists but has not been adopted in Europe as farmers dismiss it as too expensive (70). These systems would not only reduce pollution, but would also prevent escapes and stop the spread of diseases and parasites to wild fish.

The fish farm location is a crucial factor if waste effluents are to be diluted sufficiently to avoid harmful effects on the surrounding environment. Favourable sites are characterised by a deep bottom, high currents and at a minimum distance from protected species (6). These benefits are also related to moving offshore, where greater water exchange, improved dispersion and lower impact on the seabed reduce the danger of causing hypertrophic conditions (67). On the other hand, a higher degree of dispersion implies that installations moored in deep water occupy a relatively extensive seabed area and environmental effects may therefore be registered over large distances (71).

The evolution from intensive monoculture of finfish towards integrated polyculture systems has been proposed on many occasions as the way towards a more sustainable aquaculture (70). Shellfish aquaculture has indeed the opposite effect on the water column as it transforms wastes into raw material and may hence be used as a means of reducing the environmental impact of fish farming (8). Studies have shown that also seaweeds grow well in wastewater, thereby reducing nutrient and particulate loads (53). Alternatively, benthic species that are tolerant to bad environmental conditions and that feed on organic carbon, like sea cucumbers or worms, could be used in connection with intensive fish farms. A great potential is therefore seen in the development of integrated aquaculture systems, not only to reduce effluents, but also to diversify products and to increase productivity. However, the production may not be economically viable as the marketability of molluscs raised in intensive fish farming area currently is constrained by human health considerations (53).

3.19. Open ocean aquaculture

The variables characterising the coastal environment vary largely from one area to another and the many challenges faced by sea cage farming may therefore be site dependent. This wide range of problems calls upon the development of a variety of technological solutions tailored to the needs of particular production sites. While fish farms in the North of Norway may suffer from ice aggregations on the cage surface, sea cage nets located in hypertrophic parts of the Mediterranean may experience extreme fouling. Both phenomena may lead to a bad performing cage with an increasing risk for escape (due to sinking of the heavy cages). Salinity is also varying widely from almost freshwater in the Baltic Sea to 35 ppt in the Mediterranean. The higher the salinity of the seawater, the more rapidly corrosion problems may occur in steel constructions, urging for production methods taking into use different materials or more advanced maintenance procedures. Besides temperature and salinity, other important variables are water currents, wave heights and tidal difference.

Generally, sea cage farming is moving further away from the coast into more exposed water masses with a more stable environment. In its most extreme form, this open-ocean fish farming is called offshore aquaculture. Its opportunities are centred on relief from user conflicts, improved water quality and reduced impact on the surrounding natural environment (31). It is expected that about 50% of the projected increase in finfish production will come from off-shore cage farms by 2010 (21).

In Ireland and Turkey many fish farms are already operating in exposed locations mainly due to the shortage of sheltered bays and to the high demand from other users. However, truly open ocean aquaculture in highly exposed sites is still a pioneering enterprise throughout the world, experiencing a high rate of failure (4, 67). Existing offshore farms are relying on technologies which are successful inshore but are not at all suitable for the more hostile environment offshore. New technologies and competence related to transport, maintenance and operation of the aquaculture units are therefore urgently required (57).

Short period waves, along with strong winds and currents create a challenging environment for any cage system. In addition, equipment failure or human errors carry greater consequences both economically and for the environment. Containment systems must therefore be adapted to off-shore situations, demanding more robust equipment and mooring gear as well as larger and more durable working boats (71). At the same time, it must involve cage maintenance and production costs that allow offshore operations to be economically viable (43).

Based on research experiences in Ireland, three principal challenges were identified: wear and tear, feeding and harvesting. Pens and mooring configurations need to respond to the site-specific challenges, making sure that they integrate with the rest of the system and with the farm management techniques (29). However, at offshore sites, positioning is less critical as exposure and currents have less spatial variability. Therefore the use of a single-point mooring is possible, reducing the cost, maintenance and environmental impact compared to conventional multi-anchor methods (31). In the most exposed situations, there is a clear trend towards using submerged systems as these are less influenced by the strong winds and waves at the water surface (67).

Automatic feeding is vital, as frequent trips to an open ocean site are neither economical nor even possible in adverse weather. The implementation of automation, remote control and monitoring capabilities via telemetry systems for feeding and appetite monitoring are essential (69, 66). Other operations that need to receive special attention are grading, net cleaning, predation, mortality removal and equipment failure (67). Standards for documentation and certification of offshore operations also need to be developed.

Successful open sea cage technology developed for one species needs to be improved and applied according to the requirements of other species (68). Several species are suggested as candidate species for open ocean aquaculture: cobia (*Rachycentron canadum*), mutton snapper (*Lutjanus analis*), greater amberjack (*Seriola dumerili*), Atlantic salmon (*Salmo salar*), Atlantic cod (*Gadus morhua*), halibut (*Hippoglossus hippoglossus*), haddock (*Melanogrammus aeglofinus*), gilthead seabream (*Sparus aurata*), sea scallop (*Placopecten magellanicus*) (4). But fish farming is not the only aquaculture branch that is exploring the possibilities for offshore production. The development of offshore rafts and long-lines may also stimulate the expansion of mollusc farming (19).

By its very nature, offshore aquaculture production is relatively expensive involving higher capital and other fixed costs than traditional aquaculture. It therefore requires an economy of scale, rigorous management and forward planning regimes, and cost-competitive approaches that are commercially viable (67, 31).

The development of new technologies adapted for offshore farming requires the collaboration between researchers, suppliers and farmers in a business environment that does not expect a short-term return (67). The Forward Study of Community Aquaculture (18) suggested that the EU should support research on the technical constraints of offshore aquaculture as a way to obtain a sustainable aquaculture. Many challenges related to aquaculture production in exposed areas are similar to those known from the off shore oil industry. The development of open ocean fish farming might therefore draw considerable advantage from the experiences, competence and technologies from the oil sector (62). Oil and gas platforms already in place may be made suitable for use as moorings or as a base of operations for aquaculture activity and provide an accessible workspace (43).

The legal and regulatory environment surrounding the offshore aquaculture industry is cited consistently as one of the major hurdles to its development (4). Recently, the National Oceanic and Atmospheric Administration (NOAA) of the USA has made it a priority to pursue the development of large offshore aquaculture operations in the exclusive economic zone, beyond the reach of state laws (30). Then, the “National Offshore Aquaculture Act of 2005” founded the basis for the establishment and implementation of a regulatory system for offshore aquaculture in the US Exclusive Economic Zone. It gives authorization to the Secretary of Commerce to establish an integrated, multidisciplinary, scientific research and development program to further offshore aquaculture technologies that are compatible with the protection of marine ecosystems (55). Similar initiatives have not yet been taken in any of the European Member States.

4. Results – inquiry

4.1. Challenges

The relative importance of the different pre-defined technological challenges in sea cage aquaculture experienced today and in the future (2020) is illustrated in figure 4. It shows the gradient from what currently requires the most attention to what is the least prioritised today.

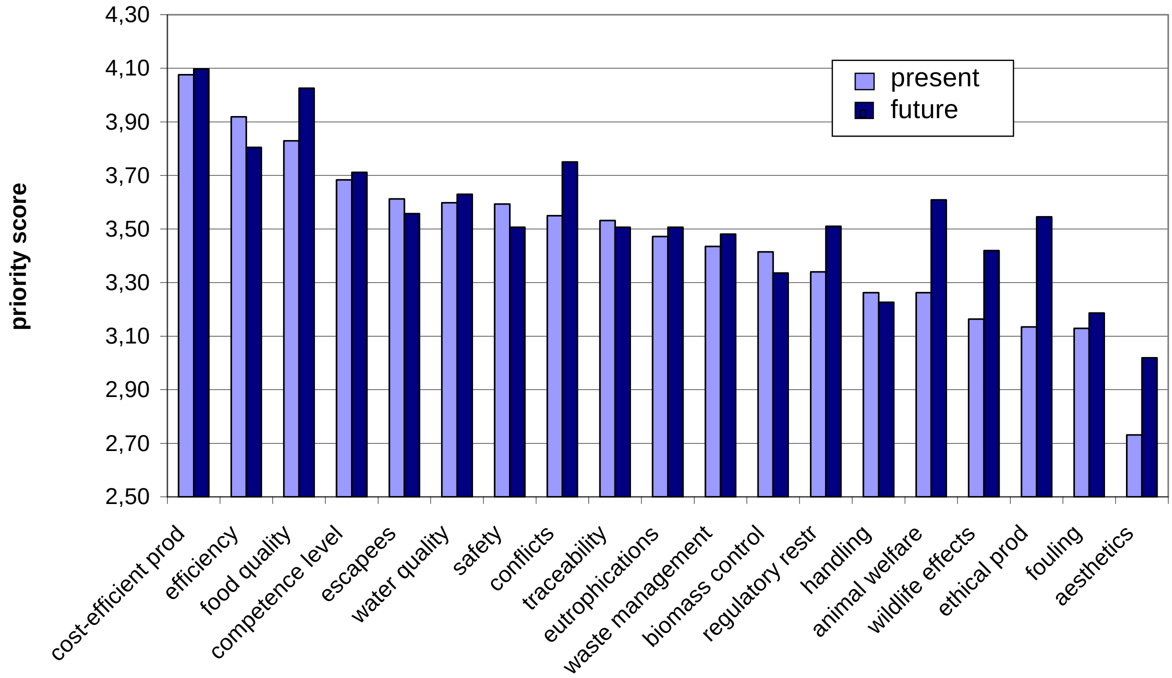
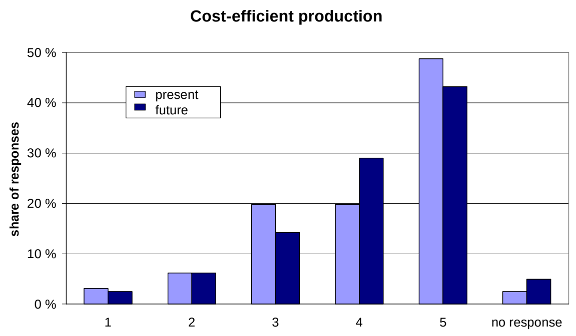


Figure 4: The importance of the different technological challenges today and what is expected in 2020 (score from 1: minor challenge, to 5: major challenge).

Cost-efficiency was clearly identified as the major challenge in sea-cage aquaculture with an average score of 3.9 (where 1 is chosen as the lowest and 5 as the highest priority). When considering warm water species, the score even reached an average of 4.3. This indicates that the production of sea bream and sea bass still has a greater potential of increasing its cost-efficiency compared to the cultivation of salmonids (score of 3.8) and shellfish (score of 3.5). The respondents involved in the production of cold-water species, which is a young sector with a great growing potential, also defined cost-efficiency as the far most important challenge (score of 4.2).

The search for more efficient operations in sea-cage aquaculture was also clearly considered to be a key challenge by a majority of the respondents. Indeed, more than 70% of the respondents gave the issue a score of 4 or higher. Again, this challenge seemed to demand more attention in the production process of warm- and cold water species (average scores of respectively 4.1 and 4.0) when compared to salmon culture (average score of 3.6). The representatives from the shellfish sector also emphasized the importance of the efficiency of operations (average score of 4.1).

The score distribution of both these issues are schematised in the figures 5a and 5b below.



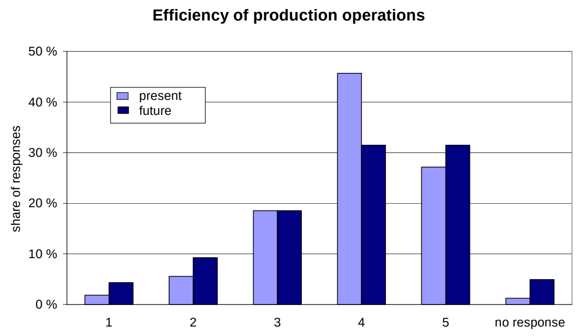


Figure 5a (left) and 5b (right) .The relative score distribution related to the importance of the technological challenges "cost-efficient production" and "efficiency of production operations" at present and in the future (score from 1: minor challenge, to 5: major challenge.

Whereas almost half of the respondents experienced cost-efficiency as a very important challenge (i.e. score 5) in today's production, this share slightly decreases when relating to the future situation. In total, the average score was almost constant (+0,5%) in time. It is therefore believed that cost-efficiency will remain a major driving force when searching for technological innovations. The efficiency of production operations, on the other hand, shows a slight decrease in average score of about 3% over time, which is noticeable for all segments in sea-cage aquaculture. This expected drop in importance over the next 15 years may point to a strong belief that the development and application of new technology and management tools will meet this challenge in the years to come.

Figure 6 illustrates the evolution in challenge significance over time, expressed by the relative change in average score from today to 2020.

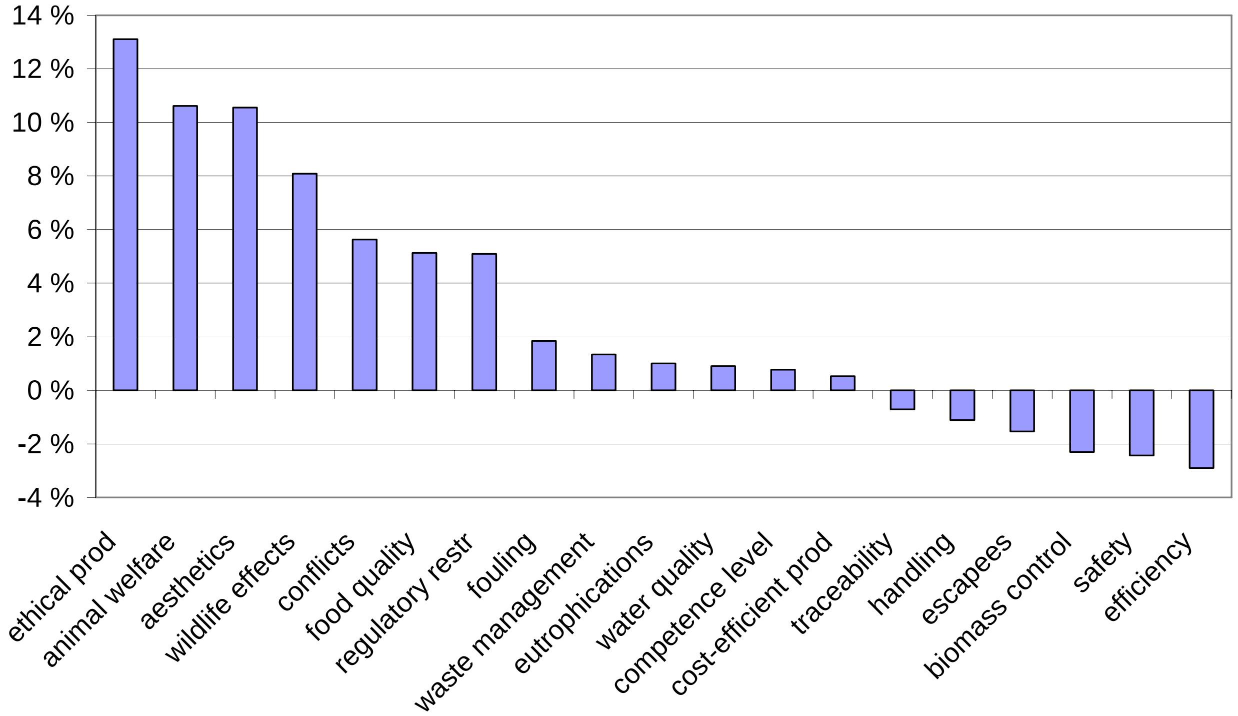
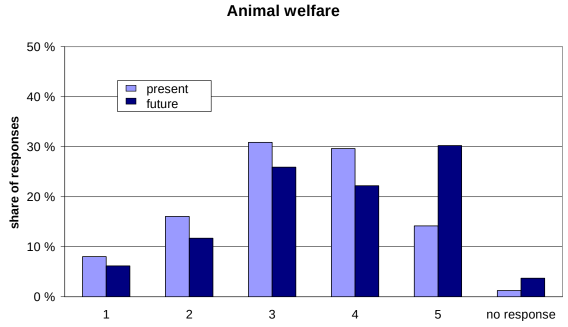


Figure 6: Relative changes in technological challenge score over time (from today to 2020).

In figure 7, the challenges with a positive change are expected to become more important in the future, and hence deserve a growing attention from the research community and supplying industry. The inquiry results show that value-linked issues such as animal welfare, ethical production and aesthetics will become increasingly important in the next decennium (see figures 7a and 7b).



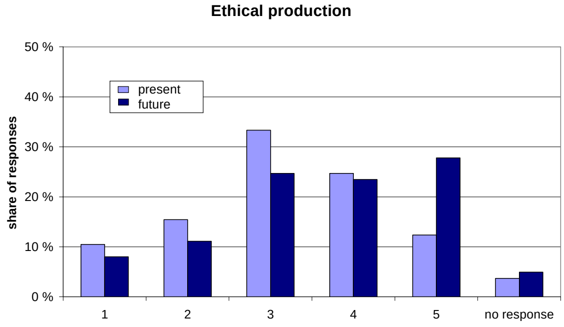


Figure 7a (left) and 7b (right). The relative score distribution related to the importance of the technological challenges "animal welfare" and "ethical production" at present and in the future (score from 1: minor challenge, to 5: major challenge).

Animal welfare was with an average score of 3.26 not experienced to be a crucial challenge in today's sea-cage aquaculture production. However, a clear trend of growing importance of the animal welfare issue was observed, and more than 30% of the respondents believe that welfare will be a major challenge in the year 2020. This result illustrates well the growing concern of the consumers for not only the quality of food they consume, but also for the well-being of the product itself. When asking to rate "ethical production" as a technological challenge, almost 60% of the respondents believed this was a minor up to average challenge. However, in the future, it is expected that ethics will become a crucial issue in the production of seafood, since more than 50 % of the respondents gave it a score of 4 or more.

While the scores related to ethical production and animal welfare as future challenges are concerned, no important differences were observed between the species groups concerned. Aesthetics, however, shows a clear distinction in challenge relevance with a higher score in warm water area's (average of 3.2) compared to cold-water area's and salmon production sites (average scores of respectively 2.8 and 2.5). It is important to have these issues in mind when developing new technology, applications and operation techniques for sea-cage farming.

Other issues, such as efficiency, personnel safety and biomass control show a negative growth, implying that there is a strong belief that these challenges will be met to a large extent by future innovations in the period up to 2020.

4.2. Technological development

Many technologies were identified to require further research and 10 out of 14 production activities received an average score higher than 3,5 (figure 8). In more than 70% of the answers, monitoring, control and cage/net technology received a score of 4 or more. This shows that these issues are highly relevant for the development of a safe and sustainable sea-cage production. As cages are getting increasingly larger, the share of fish that can be visualised from the surface decreases and additional monitoring and control is required. The trend towards more exposed sea areas demands a more robust and sophisticated type of cages and nets.

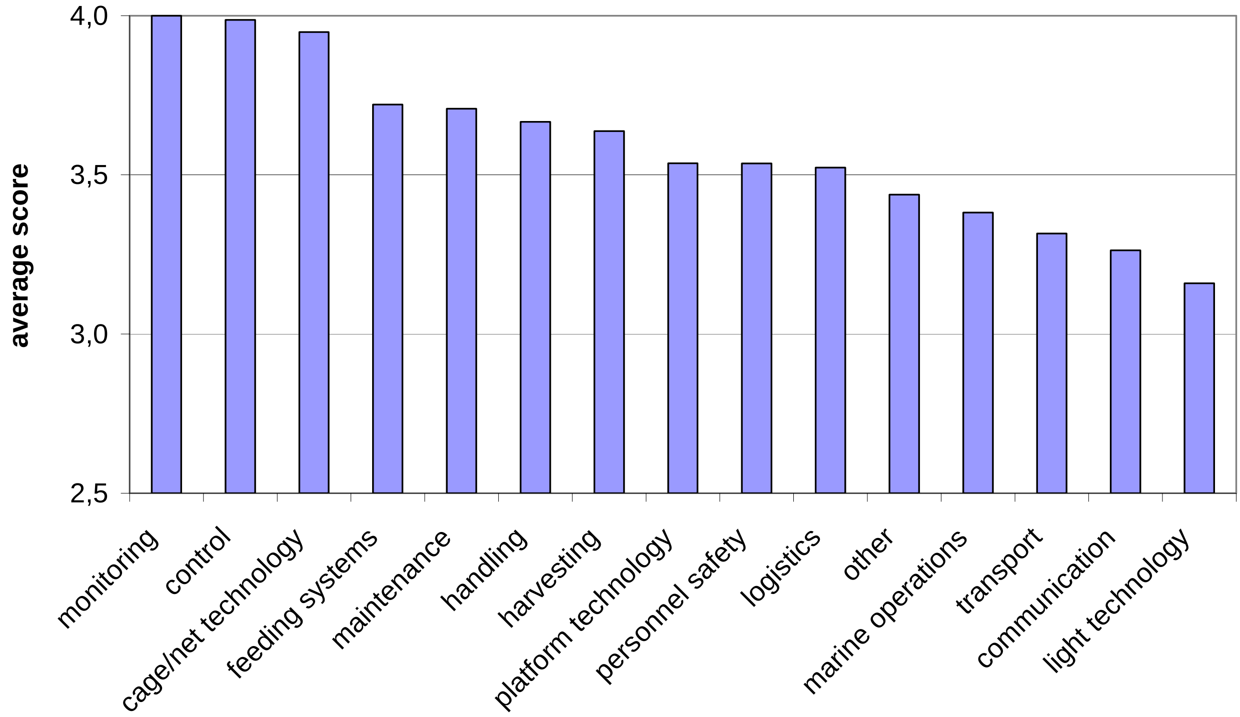


Figure 8: The average score of the technologies where further research is needed (1: low priority → 5: high priority).

4.3. Research facilities

The answers from the inquiry participants revealed that less than 50% had access to aquaculture test facilities (see figure 9).

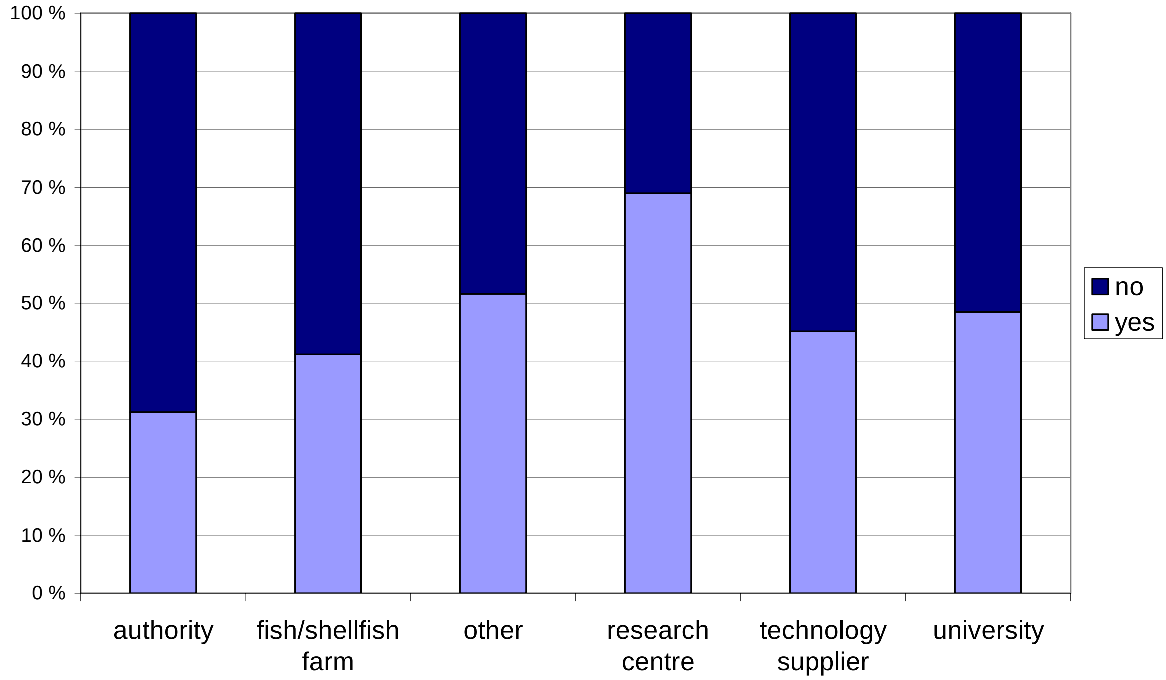


Figure 9: The percentage of respondents having access to test facilities for aquaculture research.

Throughout Europe, a number of experimental sea-based facilities are in use to promote development and innovation within sea-cage farming. Based on the data that were gathered through the questionnaire and through a supplementary inquiry among research institutes and universities, a list of the main European marine aquaculture research facilities was made. This inventory is given in Table 1 and will be used to avoid duplication and to identify potential collaborators throughout the designing process.

The infrastructures below are restricted to the European area. There are, of course, also many research facilities in other continents that may be relevant for collaboration. This may be further elaborated at a later stage. However, an institute that has already been identified as a very valuable model for the activities within DesignACT and as a highly relevant collaboration partner is the University of New Hampshire, USA. They have a clear sea based aquaculture engineering profile and offer test opportunities at an offshore site.

Table 1: Existing aquaculture sea water based research facilities in the EU (U: University; PUB RI: public research institute; PRIV RI: private research institute; COMP: company); blue areas are sea-based facilities.

		CITY	OWNER	NAME INFRASTRUCTURE	WEB SITE	TYPE INFRASTRUCTURE	EXPERTISE
1	CRO	Split	PUB RI	Institute of Oceanography and Fisheries	www.izor.hr	specialised laboratories	mariculture, environmental impact, physiology, population genetics, reproduction
1	CRO	Dubrovnik	U	University of Dubrovnik, Department of Aquaculture	www.unidu.hr	shellfish hatchery, ongrowing fields, fish culture unit	shellfish, production optimisation
2	CYP	Nicosia	PUB RI	Department of Fisheries and Marine Research (DFMR)	www.moa.gov.cy/moa/agriculture.nsf	land based marine aquaculture research station for conducting applied research	diversification, fish biology, benthic ecology, pollution
3	DK	Charlottenlund	PUB RI	Danish Institute for Fisheries Research (DIFRES)	www.difres.dk	on-land experimental facilities with recirculation systems, laboratories for digestibility, physiology	nutrition physiology of fish larvae, use of live feed, health and welfare, nutrition, growth (advice to Ministry)
4	DK	Hirtshals	PRIV RI	SINTEF North Sea Centre Flume Tank	www.sintef.dk	on-land experimental facility for testing models of fishing gear	fishing technology
5	EL	Heraklion; Faros	PUB RI	Hellenic Centre for Marine Research (HCMR), Institute of Aquaculture	www.hcmr.gr/english_site/institutes/aquaculture	land based indoor and outdoor (Faros field station) facilities: larval rearing, nursery, weaning, pre-growing and broodstock	broodstock management, hatchery technology, nutrition, control of fish development, fish diseases
6	ES	El Toruño, Puerto de Santa María (Cádiz), Agua del Pino (Huelva)	PUB RI	Centro de Investigacion y Formacion Pesquera y Acuicola (CIFPA), Regional Goverment of Andalusia	www.juntadeandalucia.es	land based facilities, specialised laboratories, pilot plants for flat fish production	optimisation of culture systems, diversification of species (fish, moluscs, cephalopods), genomics, reproduction and larval breeding
7	ES	Vilanova de Arousa	PUB RI	Centro De Investigacións Mariñas. Xunta de Galicia	www.cimacoron.org	land based facilities, experimental hatchery facilities	production optimisation of fish and molluscs, new species, pathology and parasitology, identification of mussel larvae abundance; coastal oceanography
8	ES	Punta do Couso, Aguiño	PRIV RI	Centro tecnologico Gallego de Acuicultura -CETGA, Cluster de la Acuicultura de Galicia	www.cetga.org	aquaculture pilot plant: land based facilities for larval prod, growout and reproduction;	pathology, feeding, Artemia, automation, effluent treatment, new species

						specialised laboratories	
9	ES	Mazarrón	PUB RI	Centro Oceanográfico de Murcia - Instituto Español de Oceanografía	www.mu.ieo.es/mazarron/visita.html	indoor land based rearing facilities for larvae, juveniles, on growing and broodstock; specialised laboratories	nutrition, reproduction, culture techniques for new species
10	ES	Vigo, Castellón, Puerto Real - Cádiz, Barcelona	PUB RI	Consejo Superior de Investigaciones Científicas (CSIC) - Instituto de Investigaciones Marinas; Instituto de Acuicultura Torre de la Sal; Instituto de Ciencias Marinas de Andalucía; Institut de Ciències del Mar.	www.csic.es (www.iim.csic.es, www.iats.csic.es, www.icman.csic.es)	land based rearing facilities for fish, molluscs and crustaceans and specialised laboratories	fish larval biology and nutrition, fish pathology, reproduction, physiology, genetics and nutrition, mussel culture, ecotoxicology, marine ecology
11	ES	Las Palmas	PUB RI	Instituto Canario de Ciencias Marinas	www.iccm.rcanaria.es/ , www.grupoinvestigacionacuicultura.org/	land and sea based facilities for research; experimental activities and training	fish nutrition and feeding; culture techniques for new species; new hatchery techniques; genetics
12	ES	Monte Cantabria, Murcia, Vigo, Tenerife, A Coruña	PUB RI	Instituto Español de Oceanografía	www.ieo.es	land based rearing facilities (incl. large-scale) for fish, bivalves, algae; specialised labs	nutrition; culture techniques for new species (fish, bivalves, algae), larval rearing, reproduction, genetics
13	ES	Illa de Arousa. Vilanova de Arousa	PUB RI	Instituto Galego de Formación en Acuicultura. Xunta de Galicia	www.xunta.es/conselle/pe/centro6.htm	experimental sea based facilities: sea rafts for molluscs and fish cages, computer science applications and a intertidal production area	educational purposes
14	ES	San Pedro del Pinatar. Murcia	PUB RI	Instituto Murciano de Investigación y Desarrollo Agrario y Alimentario.	http://wsiam.carm.es/imida/proyectosinves/investigacion12.htm	land based facilities	nutrition, environmental impact, production systems, new species
15	ES	Valencia	U	University of Valencia, Unidad de Zoología Marina. Instituto Cavanilles de Biodiversidad y Biología Evolutiva	www.uv.es/cavanilles/zoomarin/pages/otr_inst.htm	land based facilities, pilot plant and specialised labs	marine mammals; turtles and fish parasitology

16	F	Palavas-sur-mer	PUB RI	IFREMER - Station Expérimentale d'Aquaculture	www.ifremer.fr/toulon	land based tanks for fish and mollusc culture, recirculation systems	physiology, immunology-pathology, genetics, technology of recirculation systems
17	F	Plouzané	PUB RI	IFREMER, Laboratoire ARN	www.ifremer.fr/drvraarn	land based rearing facilities and specialised laboratories	adaptation, reproduction, nutrition of marine fish
18	F	Plouzané	PUB RI	IFREMER, METRI	www.ifremer.fr/metri/	deep wave basin, water circultation basin, laboratories for testing materials and sensors	behaviour in marine environment of materials, equipment, sub-marine vehicles, instrumentation, physical sensors
19	F	St-Pee, Donzacq, Lees-Athas	PUB RI	INRA	http://www.inra.fr	laboratory facilities	aquaculture nutrition and metabolism
20	FIN	Rymättylä	PUB RI	Finnish Game and Fisheries Research Institute (FGFRI)	www.rktl.fi	experimental sea cages with monitoring and feeding control systems; land based recirculation fish rearing facilities	fish nutrition and feeding, fish quality, physiology
21	I	Messina	PUB RI	Istituto Sperimentale Talassografico	www.ist.me.cnr.it	land based rearing installations	environmental studies, fish farming environments, monitoring
22	I	Lecce	U	Marine Aquaculture and fisheries Research Centre - DiSTeBA - Università di Lecce	http://siba2.unile.it/acquatina	land based rearing facilities (hatchery, raceway tanks), specialised laboratories	food safety and quality control, water treatment, physiology, genetics, feeding and nutrition
23	IL	Eilat	PUB RI	Israel Oceanographic and Limnological Research, National Center for Mariculture	www.ocean.org.il	land based systems for rearing fish in seawater ponds	reproduction, larval rearing, genetics, feed development, rearing systems, integrated systems
24	IRL	Cork	U	Aquaculture and Fisheries Development Centre (AFDC), University College Cork	www.ucc.ie/en/DepartmentsCentresandUnits/AquacultureFisheriesDevelopmentCentre/	Land based freshwater and marine fish rearing facilities, laboratories	growth, feeding regimes, disease, genetics, recirculation, environmental impact; coldwater fish and shellfish
25	IRL	Newport	PUB RI	Marine Institute	www.marine.ie/rnd+facilities/marine+institute+facilities/newport+research+facility	freshwater hatchery and salmon rearing facilities	salmon and trout research, feeding, vaccines, broodstock, design of facilities in commercial situation
26	IRL	Carna	U	National University of Ireland -	http://mri.nuigalway	land based small, medium and	production of ornamental fish,

				Galway (NUI/UCG), Martin Ryan Institute Carna	.ie	large-scale flow through rearing facilities, finfish hatchery, shellfish rearing and broodstock facilities, seaweed hatcheries	invertebrates, shellfish, marine finfish, recirculation technology, hatchery and system design, phycodepuration
27	ISL	Saudarkrokur	U	Holar University College	www.holar.is	freshwater and seawater land based facilities with variable salinity and temperature	selective breeding, feed and nutrition, water quality, environmental effects, fish ecology, evolution, physiology, behaviour
28	ISL	Reykjavik	PUB RI	Marine Research Institute	www.hafro.is	Land based rearing facilities for halibut, cod, turbot, abalone and new species	juvenile production, broodstock, selective breeding, cultivation of new species
29	N	Sunndalsøra, Averøy	PUB RI	AKVAFORSK	www.akvaforsk.no	Sunndalsøra: land based facilities; Averøy: experimental pens at sea, laboratories	selective breeding and genetics, nutrition, welfare and the environment, product quality, molecular biology, marine species
30	N	Hemne,Tingvol l	COMP	Aqua Gen AS	www.aquagen.no	facilities for breeding of salmon and rainbow trout	selective breeding, production of brood fish and fertilized eggs, fish health
31	N	Hjelmeland	COMP	Center for Aquaculture Competence AS (CAC) (Skretting, Marine Harvest, AKVAsmart)	www.skretting.no	commercial size salmon grow out sea based facilities	fish health, feed production and use, food safety, feed and sensor technology, production economy, documentation
32	N	Dirdal, Lønningdal	COMP	Ewos Innovation AS	www.ewos.com	salmon grow out sea based trial farms; monitoring, control and recording of water conditions and fish growth	fish feeding and feed development
33	N	Dønna	COMP	Fjord Forsøksstasjon Helgeland AS	www.fjordseafood.com	commercial sea based facilities, cranes for collection of feed losses	feed development and technology, environmental impact of feed
34	N	Gildeskål	PRIV RI	GIFAS - Gildeskål Forskningsstasjon AS	www.gifas.no	salmon and cod grow out sea based facilities	biology and technology related to e.g. feed, sea cage experimental studies
35	N	Austevoll, Matre	PUB RI	Institute for Marine Research	www.imr.no	land based experimental facilities for broodstock, spawning, hatcheries for salmon and marine cold water sp.; sea-basedfacilities	breeding, first feeding, welfare, ethology, cod larvae production, new species, fish health, physiology

						for grow out; laboratories	
36	N	Gurskøy	COMP	Nordvest Fiskehelse AS	www.nvfh.no	salmon grow out sea based facilities	bacteriology, parasitology, hematology, analyses of water quality
37	N	Kraknes, Røsneshamn	PUB RI	Norwegian Cod Breeding Centre	http://en.norut.no/	land based broodstock and larval facilities, sea cages for cod production	measuring, weighing, marking, vaccination of fish
38	N	Sandnes	PUB RI	Norwegian Institute for Nature Research (NINA)	www.nina.no	land based facilities for smolt rearing	marine, coastal and freshwater ecology, environmental and impact assessments
39	N	Solbergstrand	PUB RI	Norwegian Institute for Water Research (NIVA)	www.niva.no	salmon grow out sea based facilities, water quality database	water quality, water treatment, monitoring of algae, effects of aquaculture
40	N	Trondheim	U	Norwegian University of Science and Technology (NTNU)	www.ntnu.no	land based seawater facilities for larval rearing	physiology, nutrition, cultivation systems for marine species, shellfish
41	N	Nærøy	COMP	Pharmaq AS	www.pharmaq.no	salmon grow out sea based facilities	fish health management
42	N	Trondheim	PRIV RI	SINTEF Fisheries and Aquaculture AS - SEALAB	www.sintef.no	land based marine hatchery, environmental impact laboratory	aquaculture engineering, marine resources and processing technology
43	N	Stavanger	COMP	Skretting Aquaculture Research Centre (ARC)	www.skretting.no	salmon grow out sea based facilities	fish nutrition and feed development
44	N	Kårvika	PUB RI	The Aquaculture Research Station in Tromsø	www.havbruksstasjonen.no	land based plant, fish health laboratory, full-scale marine farm	broodstock management, larval rearing, feeding, nutrition, fish diseases
45	N	Val	PUB RI	Val Akva	www.val.vgs.no	grow out unit for salmon and trout	educational purposes
46	N	Namsos	COMP	VESO Vikan Akvavet	www.veso.no	salmon grow out sea based facilities	fish health
47	N	Vikebukt	PRIV RI	Villa AS (Cod Farm and Miljølaks)	www.leppefisk.no	cod farm and salmon grow out sea based facilities	development of production methods for cod and for salmon using wrasse as treatment against sea-lice

48	NL	Texel	PUB RI	Royal Netherlands Institute for Sea Research (NIOZ)	www.nioz.nl	large-scale land based aquarium facilities, acclimatised with running seawater and variable temperature and salinity	marine ecology and evolution in marine ecosystems
49	NL	IJmuiden	PRIV RI	Wageningen IMARES b.v. Institute for Marine Resources & Ecosystem Studies	www.rivo.wageningen-ur.nl	land based seawater tanks and aquaria	production of new fish species, nutrition, recirculation technology, bio-economical modelling
50	PL	Faro	U	Algarve Center of Marine Sciences (CCMAR), University of Algarve	www.ualg.pt/ccmar/aquagroup/	land based marine aquaculture station of Ramalhete	new species, physiology, broodstock management, production systems, feeding regimes
51	PL	Lubiatowo	PUB RI	Coastal Research Station	www.ibwpan.gda.pl/lubiatowo/	marine station with permanent measuring structures	research on coastal phenomena: waves, currents, coastal morphodynamics
52	PT	Porto	PUB RI	Interdisciplinary Centre for Marine and Environmental Research (CIIMAR)	www.cimar.org/ciimar/	land based facilities with closed circuits	aquaculture biology, nutrition and pathology, environmental impacts, integrated aquaculture, offshore mariculture
53	PT	Lisboa	PUB RI	National Institute of Agronomy and Fisheries Research (IPIMAR)	www.iniap.min-agricultura.pt	specialised laboratories (field station)	physiology, anguiliculture, mussel culture, pathology, histology, nutrition
54	ROM	Constanta	PUB RI	National Institute for Marine Research and Development "Grigore Antipa"	www.rmri.ro	long-line systems for mussel breeding, research vessel, small-scale land based rearing facilities	marine ecology and environmental monitoring and managing; marine and freshwater rearing of fish and bivalves
55	SE	Norrbyn	U	Swedish University of Agricultural Sciences	www.vabr.slu.se	land based brackish water rearing facilities, specialised laboratories and equipment	fish behaviour, feeding and nutrition, physiology, molecular biology
56	TUR	Izmir	U	Dokuz Eylül University, Institute of Marine Sciences and Technology	www.deu.edu.tr	no sea based facilities, model basin at the Technical University of Istanbul	design of offshore fish farm structures, aquaculture impact on the marine environment, fish farm planning
57	UK	Lowestoft, Weymouth	PUB RI	Centre for Environment, Fisheries and Aquaculture Scienc (CEFAS)	www.cefas.co.uk	flexible on-land rearing facilities and specialised laboratories	fish health and medical treatment, food safety, environmental impact,

							management tools
58	UK	Aberdeen, Aultbea	PUB RI	Fisheries Research Services (FRS) Marine Laboratory	www.frs-scotland.gov.uk	land based facilities: rearing facilities, challenge units and behavioural units	fish health, pathology, virology, molecular genetics, epidemiology, immunology, fish behaviour
59	UK	Scalloway (Shetland)	PUB RI	North Atlantic Fisheries College (NAFC) Marine Centre	www.nafc.ac.uk	land-based marine hatchery, sea-based facilities for salmonids, marine finfish, shellfish	brood stock management, larval rearing, on growing production, antifouling, harmful algae
60	UK	Oban	PUB RI	Scottish Association for Marine Science (SAMS)	www.sams.ac.uk	large-scale land based rearing facilities, temperature controlled rooms, specialised laboratories, seabed test area, artificial reef	environmental impacts, new species, fish behaviour, larval nutrition, monitoring equipment testing and technique development
61	UK	Stirling	U	University of Stirling, Institute of Aquaculture	www.aqua.stir.ac.uk/lsf/	on-land trout farm, disease aquarium, tropical aquarium, specialised labs	pathology, reproduction, nutrition, environmental impact, aquaculture systems

About 75% of the facilities listed above are land-based, focusing mainly on larval rearing, reproduction or fish health. The sea-based test facilities are almost exclusively linked to biological research mostly dealing with fish welfare, disease control, feeding behaviour or environmental impacts. Many of the listed infrastructures also offer laboratories with specific analytical tools for e.g. genetic identification, ecotoxicology or fish physiology.

In addition, many commercial farms are used as experimental facilities, or tests are done at infrastructures owned by the equipment supplying or feeding companies themselves. None of these conditions, however, are ideal to produce objective and reproducible results.

The need for a large-scale sea-based technology and engineering research infrastructure has been expressed by researchers from NTNU and SINTEF since many years, as research projects with a clear technological focus have been difficult to perform adequately using today’s test facilities. The latest developments in sea-cage aquaculture, such as larger production units, need for more automation and control, more exposed locations, and stricter regulations for sustainability and fish welfare, have contributed to a growing need for a research infrastructure that may promote technological innovations in the sector.

This was confirmed by representatives from other European research institutes and industrial partners. At the Aqua2006 conference in Florence, Italy, the 1.5 day lasting open-ocean aquaculture session had a mainly technological approach and attracted up to 200 attendants. Both presentations and discussions revealed that there were still many knowledge and technology gaps before a successful open-ocean production may be achieved.



Moreover, a large majority of the inquiry respondents expressed an interest to use the future facilities and to collaborate in the design of the infrastructure (figure 10).

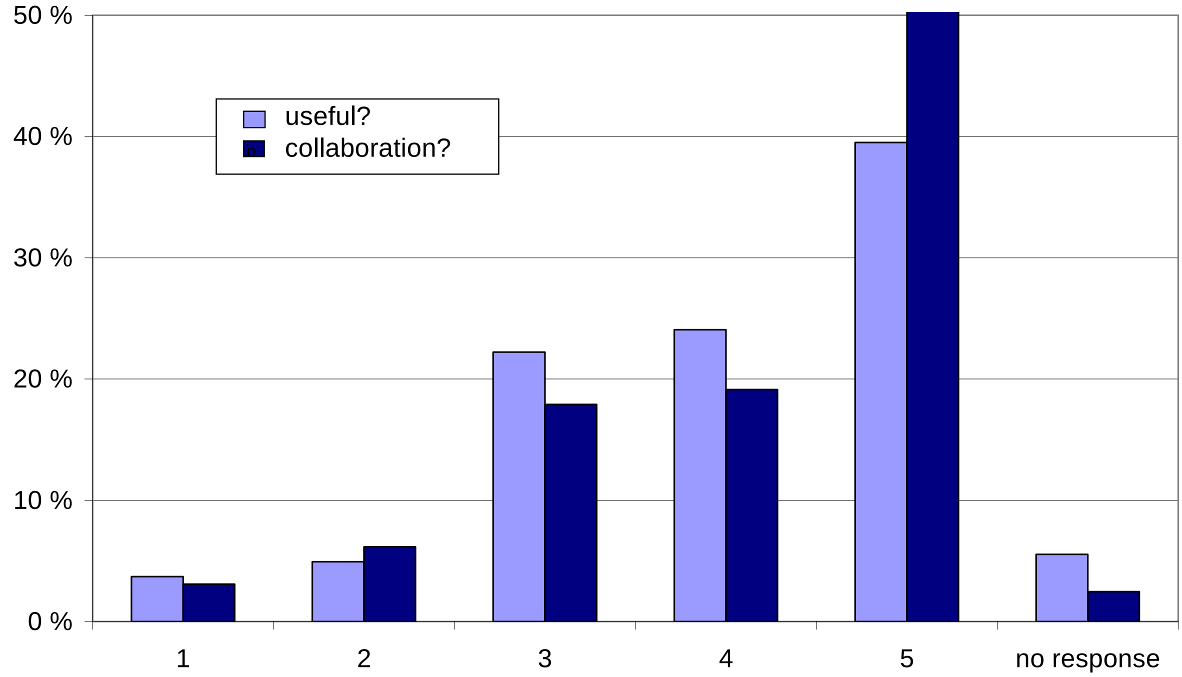


Figure 10: The percentage of scores related to the usefulness of the planned infrastructure and the interest to collaborate in the planning of the European aquaculture centre of engineering.

The experiences made in the past, along with the data gathered from the inquiry illustrate well the need for a European large-scale research infrastructure with a technological and engineering focus that may supplement existing test facilities.

The proximity of research professionals and experts in the disciplines of interest is an important determining factor for the quality of the research infrastructure. In the inquiry, 79.0% believed that the presence of experts at the facility was an important or major issue when choosing a facility to carry out experiments (see figure 11a). This was mainly so for research centres, technology suppliers and fish/shellfish farmers, with average scores of 4.5, 4.2 and 4.1 respectively. The respondents working with shellfish consider the presence of professional assistance as most important, giving it an average score of 4.5.

The possibility to monitor and control experiments from the user’s home office was not prioritised equally strong, as only 33.8% were of the opinion that this was important (score 4 or 5).

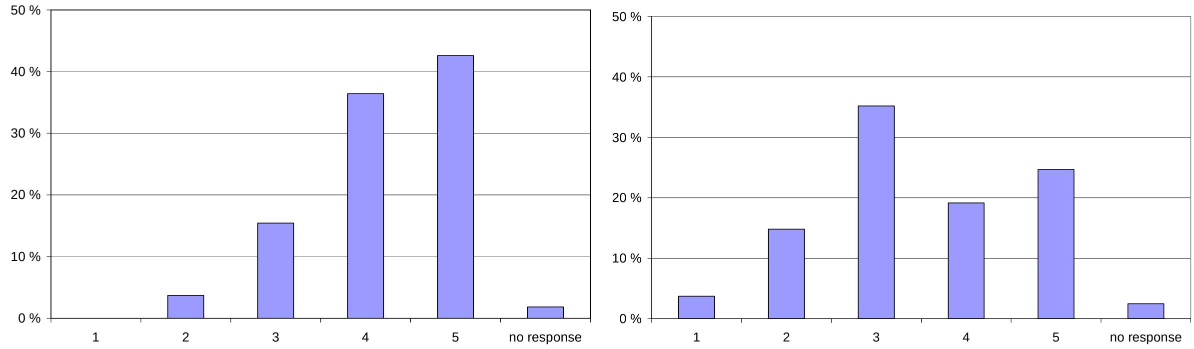


Figure 11a and 11b: The percentage of scores related to the importance of the presence of experts at the facility (a) and to need for monitoring and control of the experiments from the user's home office (b).

4.4. Open-ocean aquaculture

The belief that mariculture is gradually evolving towards more exposed areas was confirmed by the results of the inquiry. Indeed, 56.8% of the respondents were fairly or strongly convinced that aquaculture production units in their country will move towards offshore locations. Approximately a similar share of contributors, i.e. 53.1%, found the access to facilities with a different degree of exposure to physical forces such as wind, waves and current, important for their research purposes (see figure 12).

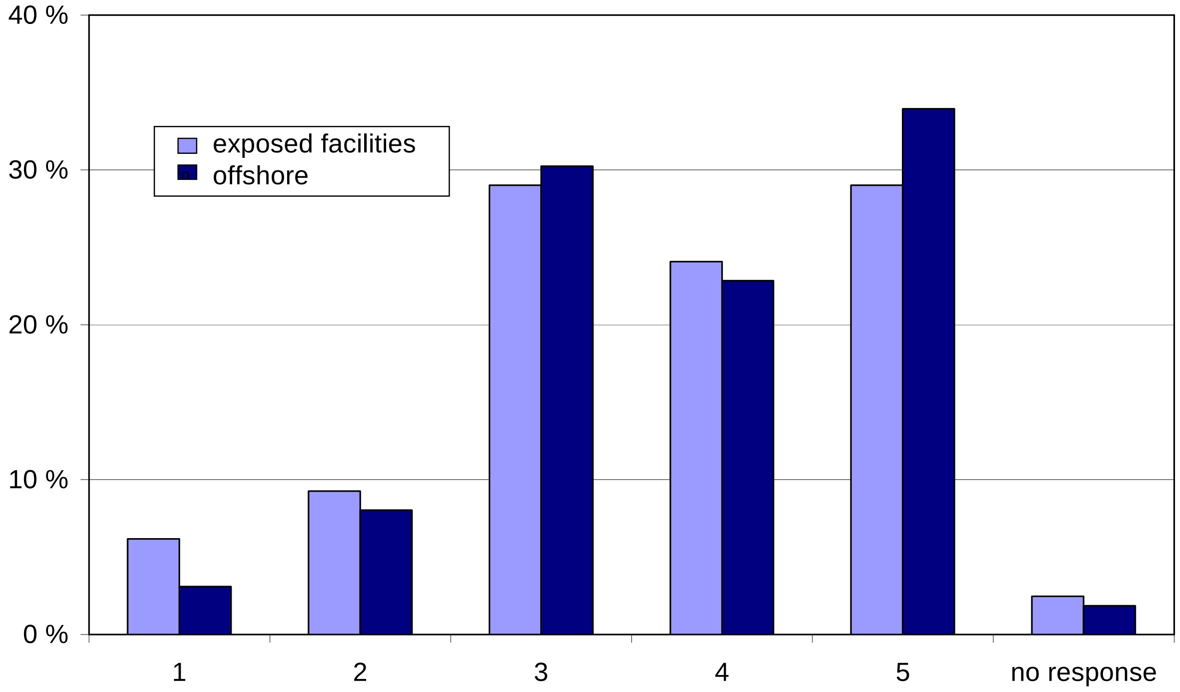


Figure 12: The percentage of scores related to the need for facilities with different degrees of exposure and to the belief of the aquaculture industry moving further offshore.

In Europe, the experience with offshore aquaculture is quite diverse. This is reflected by the data acquired from the inquiry. The respondents from Ireland, which has known a relatively long involvement with offshore aquaculture, showed the highest confidence in mariculture in exposed areas with an average score of 4.5. Also Norway and Greece showed a considerable confidence in the trend towards less sheltered locations with an average score of 3.9 for both countries (see figure 13).

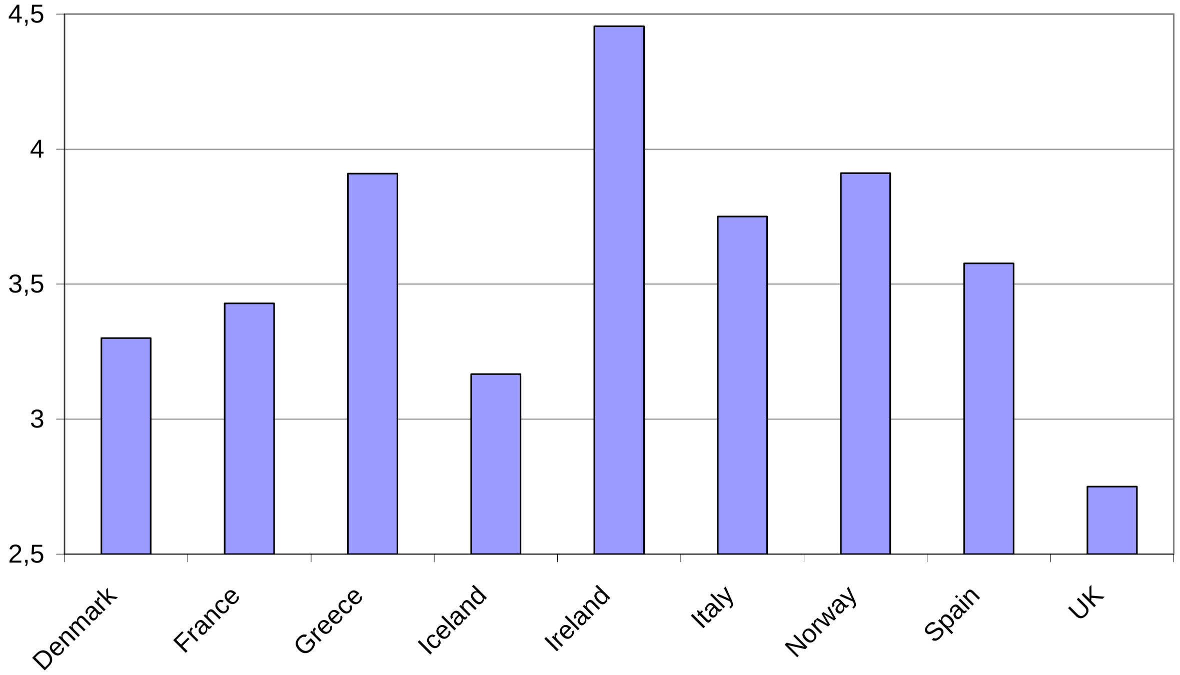


Figure 13: The average score of the belief in offshore aquaculture categorised per country (only the countries with more than 5 answers per category are shown).

4.5. Summarised results

In an attempt to visualise the obtained results, table 2 was created (see next page).

The table lists the technological challenges that were prioritised in the inquiry on the Y-axis. From the top to the bottom of the table, the challenges are ranged from the highest average score to the lowest average score.
The colours were used to indicate:

- challenges with an average score > 3.8
- challenges with an average score between 3.5 and 3.8
- challenges with an average score < 3.5

The challenges written with bold characters are those that are expected to show more than 8 % increase over time.

The values in the table indicate at which degree the technology / engineering tool is relevant for the challenge experienced:

1 the tool is little relevant for the challenge
2 the tool is medium relevant for the challenge
3 the tool is highly relevant for the challenge

These levels of relevance are evaluations done by the authors.

In those cases a high value is combined with an important challenge, the matrix cell is given a dark colour. The lower the relevance of the tools for the challenges, and the less important the challenges, the lighter is the colour of the cell.

The tools that are relevant for the challenges that are expected to become more important in the future are marked with dots / grey areas.

In this way, the table may point out the technology and engineering tools where research should be focused on. From table 2, it may be concluded that research on control systems, maintenance operations, cage / net / mooring technology and feeding systems should be prioritised in the process of meeting the most important challenges in marine aquaculture.

Table 2: The relevance of the different technologies /engineering tools for the challenges in sea-cage aquaculture that were defined in the inquiry. The total score indicates the level of priority to be given to research and innovation.

	HOW RELEVANT IS THE TOOL FOR THE CHALLENGE?	**TECHNOLOGIES / ENGINEERING TOOLS**													
		Control systems	Maintenance operations	Cage / net / mooring technology	Feeding systems	Monitoring systems	Handling operations	Harvesting operations	Logistics	Marine operations	Transport	Communication systems	Personal safety systems	Platform technology	Light technology
CHALLENGES	Cost-efficient production	3	3	2	3	2	2	2	3	3	2	3	2	2	2
	Efficiency of operations	3	3	2	3	3	3	3	3	3	1	3	2	1	2
	Food quality	3	2	3	3	3	3	3	2	2	3	1	1	2	2
	Competence of personnel	3	3	3	3	2	3	3	3	3	1	2	2	1	1
	Escapees / loss of fish	3	3	3	1	3	3	3	2	2	2	2	2	3	1
	Water quality	3	3	3	2	3	2	2	1	1	2	1	1	1	1
	Safety at work	3	3	2	2	2	3	3	3	3	2	3	3	3	1
	Conflicts of area use	1	2	3	2	1	1	1	2	2	2	2	1	3	2
	Documentation / traceability	3	2	2	2	3	2	2	2	2	2	3	2	1	1
	Nutrient loads / eutrophication	3	2	3	3	2	1	1	2	1	1	1	1	1	1
	Waste management	3	1	2	3	3	2	1	3	3	1	1	1	2	1
	Biomass control	3	1	2	2	3	2	2	3	1	1	3	1	1	1
	Regulatory restrictions	3	3	2	3	3	2	3	2	2	2	1	3	1	1
	Handling	1	3	2	2	3	3	3	3	2	3	1	2	1	1
	Animal welfare	3	3	3	3	2	3	3	1	2	3	1	1	1	3
	Direct effect on wildlife	2	3	2	3	1	2	2	2	2	1	1	1	1	2
	Ethical production	3	3	3	2	3	3	3	1	1	2	1	3	1	2
	Fouling	3	3	3	2	3	3	1	2	2	1	1	1	2	1
	Visual and odour impact (aesthetics)	1	3	3	3	1	1	1	1	2	1	1	1	3	3

5. Discussion

The main drivers for the promotion of technological innovation in sea-based aquaculture have been identified as:

- increased competition with other protein sources and other regions
- the consumer's growing interest for safe and healthy food
- increased requirements for sustainability
- increased competition for space in coastal areas
- the creation of a safe and attractive working environment

Through the analysis of trends in sea-cage aquaculture and through the input provided by the DesignACT inquiry, the main needs for knowledge and technological innovation were identified.

1. A cost-efficient production and a high efficiency of the marine operations were the most important challenges currently experienced. These may be met by a further intensification, automation and up scaling of the production. This again requires well-developed operational routines at sea, accurate measuring systems for monitoring of the enclosed biomass, and reliable control mechanisms. The development of control mechanisms may lead to a further automation and an increased cost-efficiency.
2. The growing awareness for ethics and aesthetics pushes forward the need for production systems that safeguard animal welfare and that take sufficiently care about the preservation of the surrounding environment. In intensive mariculture, good water quality, responsible handling routines and minimisation of escapes are important objectives towards a sustainable production. This may be achieved by improved containment systems.
3. Harsh and dangerous working conditions in rural areas make the mariculture industry a little attractive sector for the engagement of young professionals. Technology to advance the safety on aquaculture platforms and a further automation of high-risk operations may contribute to make the profession more appealing.
4. The gradual movement of production units towards more exposed areas has been initiated through the search for locations with more stable environmental conditions and less conflict with other coastal activities. New challenges in comparison to mariculture in sheltered areas are the development of more robust equipment as well as a larger degree of automation for operations such as feeding and maintenance.

The results of the inquiry reveal that the mariculture industry is still facing a wide range of technology related challenges on its way towards an optimisation of the efficiency and sustainability. The challenge level showed a variation between the different aquaculture segments (i.e. sea-cage production of cold and warm water species, and salmonids). Issues such as efficiency of the operations, food quality, cost-efficiency and traceability, were experienced as a greater challenge in the production of marine species compared to the aquaculture of salmonids. Northern Europe, represented by salmonids and cold water species, expressed a stronger need for focusing on topics such as ethical production, animal welfare and escape. It is generally expected that the segments with the longest experience in commercial mariculture production will be the first to meet the new challenges. The promotion of exchange of knowledge and experience between the different species groups may prove to be a very valuable step towards advances in all sector segments. The use of a joint research infrastructure for technology and engineering together with the development of

European standards and benchmarking systems to assess and certify the qualifications of technological tools are important contributors to this development.

A clear interest is shown in a European large-scale research infrastructure with a focus on technology and engineering in marine aquaculture. The inventory illustrates many existing aquaculture facilities, but none are offering cross-disciplinary research opportunities at sea on a large scale. Collaboration with existing centres of expertise is vital. The presence of experts in the field of aquaculture engineering who directly support the research facilities was clearly seen as an essential feature of the future research infrastructure.

Aquaculture production at sea has in common with the large shipping and oil industries that it is dependent upon basic knowledge of the marine environment and of its effect on ships, constructions and appliances located in the sea. The transfer of expertise, know-how and research results between those sectors may stimulate technological progress in the aquaculture industry. An exploitation of knowledge in fields of materials technology, information and communication technology, cybernetics, production technology and oceanography is equally important for the sector.

As a means of summarising the results of the inventory and to facilitate their implementation in the design of the new aquaculture engineering research infrastructure, table 2 has been created. Its X-axis lists the technologies that are relevant for sea-cage farming, from those receiving the highest (left) to the lowest (right) research priority. The Y-axis gives an overview over the challenges that have been defined in the study, related to production, personnel and environment. The challenges that were identified as major issues received that darkest colour, while those not so relevant are not coloured.

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