Comparative study of two grow-out models for Atlantic salmon: cage and recirculating systems producing 1,000 T a year

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ABSTRACT

Thanks to geographical conditions ideal for large scale cage aquaculture, Scottish Salmon Industry has grown incredibly in the last 20 years to reach more than 170,000 T in 2003. Despite strong improvements in all parts of the rearing technology, the scale of the industry raises fears among environmentalists, risks for producers and more restrictive legislative evolution while consumer perception of Scottish Salmon quality needs to be maintained. For many professionals within the industry, the diversification of rearing systems appears necessary with the choice of investing in more off-shore or in inland technologies. In order to assess the comparative profitability of both systems, a technical design of a circular cage site located in a medium exposed area and a recirculating system (RAS), 70 % recycling, made of 5 individual systems have been developed on the same scale (1,000 T/year). With production costs of respectively £2.04/kg and £2.12/kg (Operating costs and depreciation), the preliminary designs and management analyses are consistent. Capital Costs are £2,060,000 and £4,103,000 to set up respectively a cage and a recirculating system while Operating Costs are close at about £1,800,000. A basic financial analysis shows that the cage system is far more profitable if sales price of whole salmon is identical for both systems. If environmental costs are internalized, the cage system is slightly less profitable. If risk cost is included, the cage system remains more profitable despite greater risks in operation. Variation of biological performance has only a minor impact on comparative profitability of both systems. However, from a premium price of 15 % on sale price of RAS salmon, RAS system has a greater profitability with a payback period of 4.2 years and a Net Present Value of £204,100 at 10 years. This premium on price could be obtained from greater freshness, regularity of outputs, reduced transport costs, environmental respect and new localization. RAS system needs a strong investment capacity and specific management ex-farm but has a real potential for high returns in the medium and long-term.

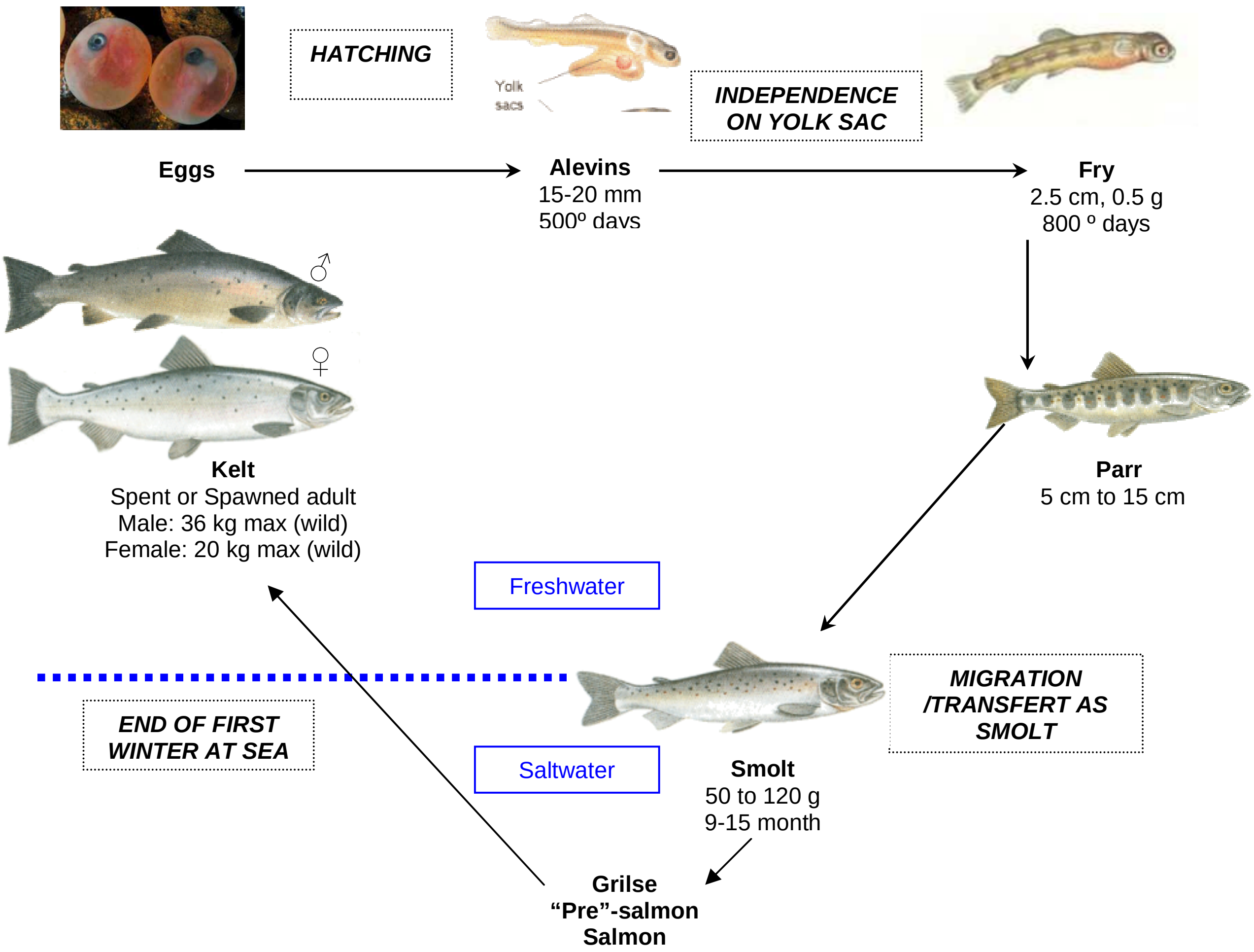
1. Introduction: Atlantic salmon Aquaculture in Scotland

1.1. *Salmo salar* L. rearing

The production cycle of Atlantic salmon is closely based on the natural life cycle provided in appendix A (Appendix A: Biological presentation) and summarized on figure 1.1.

1.1.1. Life and production cycle overview

Figure 1.1: Life and breeding cycle of Salmo salar, Atlantic salmon



From fertilization to first feeding, rate of development is entirely dependant upon temperature. Next to fertilization, eggs are referred to as green eggs which become eyed-eggs after 245 degree-days. Eyed-eggs mature for 265 degree- days then hatching begin and last for 2-3 days. Alevins or yolk-sac fry are reared in complete darkness and do not feed until 90% of the yolk-sac is absorbed, 290 degree-days after. A total of 800 degree-days is needed from fertilization to first feeding. The early success of the weaning will give a good start to the fry, a critical factor for successful smolt production. The fry well established on food grow quickly to become Parr at about 5 cm to 15 cm long. The smoltification process is under internal (nervous and endocrine) and external (photoperiod and temperature) synchronization. In farmed conditions, time to smolt is reduced to 9-15 months to produce mainly 50-80 g S0+ and S1 smolt by day length manipulation. The former smolts in the autumn of the year of hatching while the latter smolts in the next spring. This transformation is a pre-adaptation for life in marine environment and must be followed by a transfer to the grow-out facility in salt-water. S2 smolt are poorly produced, they are often culled due to the unit cost of production, their disease sensitivity in their second spring/summer and the occurrence of precocious males (Jack). However, they could decrease considerably the grow-out period at sea.

1.1.2. Water quality parameters for adult rearing at sea

Tarazona and Munoz, 1995, reviewed the key water quality parameters for salmonid culture, presented in table 1.1. Toxic levels of various harmful chemicals (heavy metals, pesticides, petroleum spills) are not addressed.

Lethal effects and sub-lethal effects

Recommended levels suggested below provide salmonids with an optimal environment to perform at best. If any factor is less than optimal, it will induce a metabolic cost and/or a stress response. This is defined as a sub-lethal level which can have 2 types of effects: reduced growth (somatic and gonadic) and susceptibility to infectious diseases (bacterial, viral, fungal and parasitic) (Tarazona and Munoz; 1995). When water conditions are severe, parameters can reach lethal concentrations resulting in mortalities.

Table 1.1: Recommended level of common water quality parameters for salmonid culture

	A	B	C
Dissolved oxygen (ppm)	> 5.0	>5.0	*Sub-lethal: 4.0-6.0* >6.0
Unionized ammonia (mg N/L)	<0.02	<0.02	<0.02
Nitrites (mg N/L)		<0.01	If 1 mg/L chloride: <0.01 If 10 mg/L chloride: <0.09
Nitrate (mg N/L)			<400
Suspended solids (ppm)	<30	<80	<20 mg/L
pH	6.4-8.4	6.7-8.6	6.0<<9.0
Sulfide (ppm)		<0.001	<0.002
Temperature (°C)	16	10-18	
Free carbon dioxide (ppm)			*Sub-lethal: 12-50* <12

A: Bromage and Shepered, 1988; B: Pillay, 1990, C: George, 2003

1.2. Scottish Salmon Industry

Salmon farming began in 1830s in Scotland to enhance recreational fisheries (Williamson and Beveridge, 1994*)* followed by Pacific North in late 1870s (NRC, 1996). Farming for food started in the 1960s in Norway, followed by Scotland, Ireland then by Canada, United States, Australia, New-Zealand and Chile. The latter is now the world's largest producer, beyond Norway**,** the historical leader. Atlantic salmon accounts for nearly 90% of farmed salmon production and has long out-stripped capture fisheries of this species (Telfer and Beveridge, 2002). Salmon provide 40% of Scotland`s food exports per annum per value (SQA, 2002)

The following section (1.2.) is mainly based on the Scottish Fish Farms Annual production survey: 2002 from *Fisheries Research Services* (SEERAD, 2003) and the Scottish Economic Report: March 2004 from *Scottish Executive* (Henderson B. & Mc Bean C., 2004).

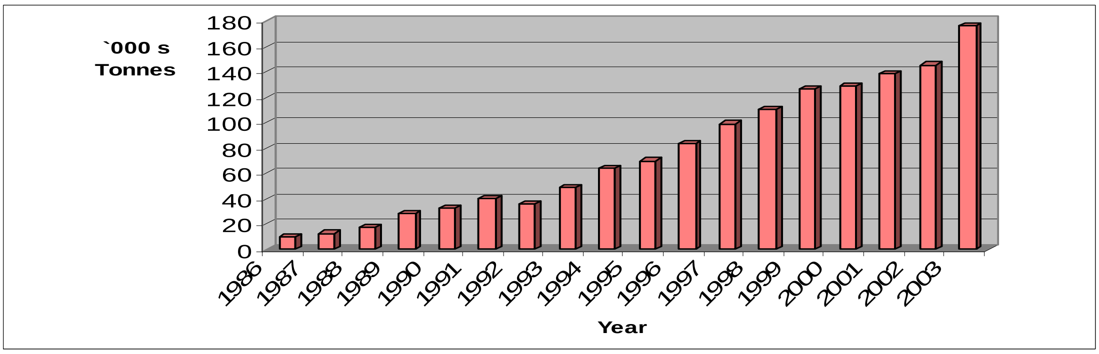
1.2.1. Output

Production level

In 2002, 328 sites owned by 84 companies produced 145,609 tonnes of Atlantic salmon. This production has more than tripled in 10 years. Since 1986, growth averaged 21 % per annum but this rate slowed over time with 5% increase per annum between 2000 and 2002 (figure 1.2)

The predicted volume of 176,596 tonnes in 2003 (based on 2002 stocks) would be the greatest 1 year increase in tonnes produced: + 30,987 T.

Figure 1.2: Scottish annual production of Atlantic salmon since 1986



Among those 328 grow-out sites, only 2 are seawater tanks (pump ashore) and none are recirculating. With a total capacity of 15,734 m³, the ratio of production to cage capacity (kg/m³) was 9.4 in 2002, slightly increasing with years. This ratio is an average across the industry and does not represent the peak biomass at harvest due to a large number of farms with no harvest in the year but included in the total capacity of the industry (table 1.5). However, active sites reach a stocking density of about 15-20 kg/m³ at harvest as recommend by SQA.

Production per class

In 2002, only 0.6 % of smolts stocked were harvest during the same year at a mean weight of 3.0 kg. Class year 0 is therefore not significant. The 1 year class is dominant with 63.4% of the production in 2002. This class reached a mean weight of 3.9 kg in 2002, slightly less than 2001 (4.2 kg) (Table 1.2). Finally, the proportion of 2 year class (mean weight: 4.8 kg) increase with 36% of the production against 29.4 % in 2002 and 2001 respectively.

Table 1.2: Salmon weight at harvest per year class (kg)

Year class	2000	2001	2002
2	4.3	4.5	4.8
1	3.9	4.2	3.9
0	3.5	2.2	3.0

Survival

The total percentage of individual harvested against stocked was 73.8 % in 2002, slightly better than in 2001 but 2.8 % less than in 2000 (76.6 %). The best survival rate was registered in 1995 with 91.5 %. This is also a global average which includes individual heavy loss. In 1995, probably few heavy losses occurred since the typical survival rate of salmon among the cycle in cage system is rather 90 %. A negligible mortality is often claimed by salmon cage farms (0.5 %, R. Hawkins, *Marine Harvest Leven Salmon*, cage farm manager, pers. com.). However, this rate probably does not include early mortalities from incomplete smoltification and Infectious Pancreatic Necrosis (IPN), fish none recovered (escapes, predation) and fish mortality in well-boat after harvest. Those mortalities sources are cited by C. Wallace (*Marine Harvest,* Regional Health manager-south mainland, pers. com.)

Fallowing

A fallow period at the end of the production breaks the cycle of disease or parasitic infections but also allows for nutrient dispersion, processing and benthic community regeneration. From the 328 actives sites recorded in 2002, 99 had no fallow period in 2002. With a typical production cycle from 14 to 24 months and a widespread practice of single cohort rearing per site, they are mainly site with no stock movement. Almost 26% of registered sites had a fallow period of 4 to 8 weeks and 26% of 8 to 26 weeks in 2002 (Table 1.3). The median practice seems to be 8-9 weeks of fallowing before restocking (SQA recommend a fallowing period of 6 weeks minimum).

Table 1.3: Cage sites employing a fallow period: number from 2000 and proportion in 2002.

		Fallow period (weeks)						
		0	**1-4**	**4-8**	**9-26**	**27-51**	**52**	**Total**
2000		74	23	61	86	25	75	344
2001		80	10	76	94	15	45	320
2002	**No**	99	8	85	85	24	27	328
	%	30.2	2.4	25.9	25.9	7.3	8.2	100

1.2.2. Staffing and productivity

In 2002, 1306 persons were directly involved in adult salmon rearing, 49 more than in 2001. These jobs are concentrated around the coasts of the more remote parts of Scotland where limited alternatives exist, which increase their relative importance. Moreover, the estimated employment of the overall sector, including processors and combined jobs is estimated at 8600 full-time equivalent jobs in 2002. While the level of output increases (table 1.4), the level of employment remains relatively static. Therefore the productivity per workers, a measure of efficiency and profitability, continues to increase each year to reach 111.5 t per person in 2002. This is almost four times more than 10 years ago.

Table 1.4: Number of staff employed in salmon production

	1992	2000	2001	2002
Full-Time	*985*	1141	1066	1083
Part-Time	*275*	256	191	223
Total staff	*1260*	1397	1257	1306
Productivity (t/pers.)	*28.7*	92.3	110.2	111.5

1.2.3. A maturing industry

Scale of production

Table 1.5 shows the trend toward larger but also fewer sites and companies. In 2002, there were 32 new sites with a capacity exceeding 201 t but an overall reduction by 18 sites.

Table 1.5: Number of site per capacity, total sites and companies involve in salmon culture

	SITES - Production capacity (t)								**Companies**
	0*	**1-50**	**51-100**	**101-200**	**201-500**	**501-1000**	**>1000**	**Total**	**Total**
2000	183	8	20	15	40	40	40	346	90
2001	148	9	4	28	41	39	51	320	87
2002	131	10	10	25	50	51	51	328	84

** This category 0 refers to farms stocked but having no production*

In 2002, 57.5% of the salmon were produced in sites with an output in excess of 1,000 t and 26.6% in farms with an output between 501 and 1000 t. In term of companies, 18% of them (15) produced together 76% of the Scottish salmon (Table 1.6).

Table 1.6: Number of companies, production, manpower and staff productivity per group of production capacity

Prod. Capacity (t)	0-100	101-200	201-400	401-700	701-1000	1001-2000	>2000
No of companies	24	4	11	9	7	14	15
No of tonnes	346	650	3,464	4,898	6,215	18,892	111,144
Total manpower	49	19	69	56	103	167	843
Productivity (t/pers.)	7	34	50	88	60	113	132

Table 1.4 previously addressed shows the increase in staff productivity with time while productivity also increases greatly with scale, from 7 t/person to 132 t/person (Table 1.6). The gain in productivity is mainly due to economies of scale followed by technical and biological improvement.

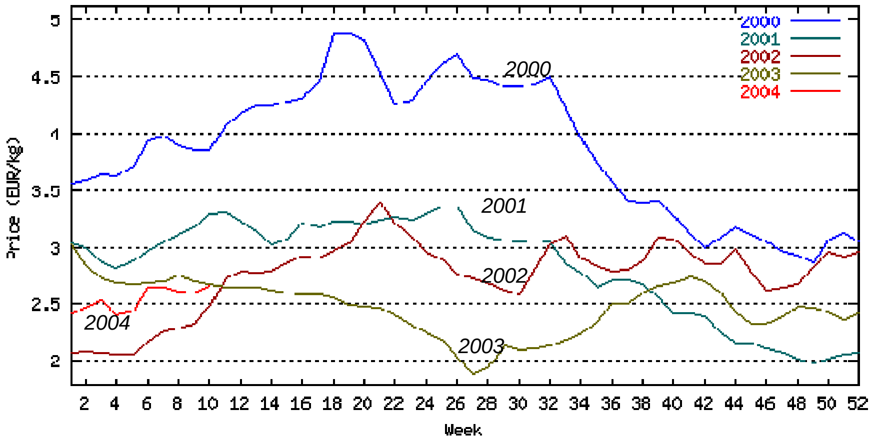
This productivity gain reduced the cost of production enabling a lower sales price at consumer level, hence stimulating demand. The industry invests in additional output, larger farms having larger investment capacity and competitive advantages. They gained market share at the expense of smaller ones and the evolution continues. This is typical of a maturing and consolidating industry. It raises the barrier to entry for potential new comers since they need to penetrate the business at high capital cost with higher economics and technical risks.

Sales Price

The previously described evolution is mainly continuous over the years but periods of major market disequilibrium accelerate industry restructuring. Total salmon exports from Norway in the first 10 months of 2003 were up 16 % to 331,000 t while Scottish salmon production increased by 21% in 2003. Supply has grown faster than demand, with flooding of traditional markets resulting in a strong price falls on the European market. While the average price of whole fresh Atlantic salmon (> 3 kg) was € 3.8/kg in 2000, it reached € 2.5/kg in 2003 with a maximum of € 2.8/kg in January and a lower level of € 2.0/kg in July 2003 (figure 1.3). Prices have slightly increased since, but remain below break-even levels for most producers. Moreover, European salmon exports to Japan were reduced due to Chilean competition. Chile has a limited domestic market, they add more value to their product and remain the preferred supplier of the largest and most lucrative market: Japan (Bjørndal, 2002).

This situation eliminates the weaker companies and accelerates restructuring to further cut costs and get margins back. However, repurchase limits effects of bankruptcies on production volumes and farmers tend to increase volumes in anticipation of an improved market. Therefore, prices improved slowly in 2004.

Figure 1.3: Fresh Atlantic salmon (whole, 4-5 kg) price, Oslo market *(www.intrafish.com)*



Prices for salmon over 3 kg are similar. Prices for 1-3 kg salmon are about € 0.6/kg cheaper on average

1.3. Environmental Interactions

The success of the salmon industry is based on the ability to produce a high quantity of fish with relatively low technical and financial requirement: Cage aquaculture. The main characteristic of this system is the free exchange of water between the rearing system and the environment. As a result, the wastes discharged from the cage freely enter the environment while cages are fully dependent on the environment characteristics.

1.3.1. Organic waste of dietary origin

Commercial salmon farming rely on a complete diet mainly made of fish concentrate (meal and oil). Therefore, a considerable biomass of feed material is introduced to a relatively small area of the cages. A proportion of those nutrients is discharged and constitutes a net addition to the environment in the form of eutrophicating substances potentially causing primary production, algal bloom and related hypoxia increase, shift in the food web structure and ecological simplification. (McClelland and Valiella, 1998; Ingrid *et al*, 1997; Worm *et al*, 1999).

Solid waste

Ingestion is dependent upon a sequence of events in which fish must recognize, reach, be motivate to eat and finally swallow the pellet. In cage system using nutrient rich dry food, uneaten food still constitute 5-15% of quantity dispatched including 1-5% of dust since periods of strong current and reduced cage volume are unavoidable (Telfer, 2004; pers. com.). An estimation of faeces ranging from 25 to 30% of the feed consumed is accepted for salmonids (Westers, 1989; Iwama, 1991), and is probably reduced nowadays. Those particles will settle to seabed, just below the cage or up to 1.2 km from the site (Holmer, 1991) depending on hydrographic conditions and waste density. Underlying sediments undergo physicochemical changes and related biological shift due to organic enrichment (Carbon, Nitrogen). The community structure is simplified toward tolerant organisms which nevertheless process waste. However, excessive enrichment can lead to anaerobic conditions, wastes are no more processed and water quality declines at depth. On a larger scale, effects of food web modification and habitat fragmentation are unknown. Time for benthos recovery has been reported from few months to 5 years (Mazzola *et al*, 2000; McGhie *et al*, 2000).

Liquid waste

Liquid dietary wastes (urine, excretion, nutrient leaches) are readily available. Feed composition as greatly improved to maximize retention, P content has been largely reduced while N excretion is minimized by optimizing protein:energy ratio (Cho and Bureau, 1997). However, it also increases the N/P ratio with potentially detrimental effects. In 1974, 1 t of farmed salmon released 129 kg total nitrogen and 31 kg total phosphorus (N/P = 4.2) (Folke *et* *al*, 1992) reduced to 50-60 kg total nitrogen and 7-9 kg total phosphorus (N/P = 6.9) in 1990s (Enell and Ackefors, 1991). As a general figure, almost 50% of the phosphorus intake and 10% of the nitrogen intake are released in the environment (Cho and Bureau, 1997).

In marine environment, there is little evidence for hypernutrification from fish farming due to dilution (Muller-Haekel, 1986; NCC, 1989; Gowen, 1990; Weston, 1991; Aure and Stigebrandt, 1990). Folke *et al* (1992) have attempted to estimate the environmental cost of eutrophication in term of N and P release. Their analysis was based on existing sewage treatment plants to find the marginal cost of reducing the load by 1 kg of N and P, which is respectively about US$ 8.5-16.5 and US$ 3.5-5. They obtained the cost of eutrophication per kg of salmon produced: US$ 0.65-0.75. By internalizing this cost, they find a total production cost in excess of the highest price paid for salmon in the 1980s. They conclude that the industry is unsustainable ecologically and economically with its present behavior. However, this analysis does not consider other options as it should be.

Algal blooms arise from a combination of advantageous environmental conditions: increase in light and temperature, water stratification and poor mixing, nutrient enrichment and adequate N/P ratio. The occurrence of Harmful Algal Blooms (HABs) in the vicinity of net pens is reported (Wildish *et al*, 1990; Martin *et al*, 1999; Whyte *et al*, 1999) but without indications on farming responsibilities. An increasing problem is the jellyfish wrap. Their ability to sting and inject toxin causes direct damage, they may also clog the net compromising water flow depending on their size. Sporadic encounter might cause low but regular mortality. Protective curtains induce poor water exchange and relocation is often difficult due to regulation and sea-bed licenses. Over the last two years, losses due to jelly-fish and toxic algal blooms in Scotland are estimated at £32 million, with slightly more than 4 million fish lost in 2001 and 2002. This amount is comparable to the cost of combating sea-lice. Insurance claims for incidents due to environmental impact, algal bloom and jelly fish doubled from 1999-2002.

1.3.2. Micro-organisms and parasites: pathogens

Naturally occurring pathogens find a reservoir of hosts on the farmed biomass from which they enhance their survival and reproduction: the farm acts as a multiplying vector of local pathogens. With environmental stress such as crowding or water quality variation, outbreak of diseases can occur in the stock with consequent losses for the farmer and increased pathogen load for wild organisms. While disease outbreaks in wild salmon rarely occur (St Hilare *et al*, 2001), sub-lethal effects are unknown such as consequences of precocious return to freshwater or osmoregulatory imbalance from sea-lice (Bjørn *et al*, 2001). Moreover, pathogens (*Aeromonas salmonicida, Vibrio salmonicida)* fill natural reservoirs (marine plankton, scallops, sediment) and may re-infect stock after treatment. (Husevåg, 1994; Nese and Enger, 1993).

Sea-lice are a serious problem for most farms and cost the Scottish salmon industry between £20m and £30m per year nowadays. By building a hypothetical case (20 cages farm, 200,000 smolt stocked, 764 T of salmon produced, salmon sales at £2.00/kg), Sinnot (1998) estimated the total loss related to a sea-lice outbreak:

Figure 1.4: Cost of sea-lice outbreak (Sinnot, 1998)

Cost of mortality:
From treatment (3% stock) and secondary infection (1% stock) = £11,000
Cost of growth lost (starvation):
Lost of 200g/fish or 40 T = £80,000
Cost of stress (Anorexic and metabolic stress):
FCR increase of 0.05 over the cycle: Extra feed cost = £30,500
Cost of harvest grade down (skin damage):
1% stock from Superior to Ordinary grade: penalty of 50p/kg = £7,400
Cost of bath treatment
6 baths * 20 cages * £500/bath= £60,000
TOTAL: Between £94,000 and £200,000 with conservative assumptions

The highest losses result from the starvation which may be up to 30 days of the production cycle (Stead and Laird, 2002). Preventive treatments are limited in their efficiency while remediation is heavy and expensive. Emergency harvest is sometimes realized increasing the production cost per kg of salmon. However, the probability and severity vary greatly with site and husbandry.

Infectious Pancreatic Necrosis (IPN) is another significant source of loss for the industry. In Shetland, 2000, 20 % to 30 % of smolts transferred died (£2 millions), fallowing did not appear to help probably due to wild finned fish or shellfish reservoir and vaccine trials have shown little protection (Sandison, 2001).

1.3.3. Feral animals

Cages are more prone to accidental release than other systems due to day to day management at sea, storm damage or vandalism (Beveridge, 1996). The number of seawater Atlantic salmon escapes reported was 367,405 fish from 13 declarations in 2002 (SEERAD, 2003) which is thought to be an underestimate. Farmed salmon appears in fisheries in levels as high as 50% of landing in Norway (1997) and 60% in Faeroe island (1998) (Hansen *et al*, 1999). Escapes can potentially alter the host environment but this is rarely demonstrated. A greater threat is that they interact on native biota through competition and predation (Beveridge, 1996). While the impacts of non-native species on the native biota are usually irreversible (Arthington and Blühdorn, 1997); in their native range they may replenish the stock of wild salmon. However, there is fear on genetic degradation of wild stocks. While the farmed salmon genome is composed entirely of naturally occurring genes, it has been suggested that farmed Atlantic salmon now represents a new identity, *Salmo domesticus*, which exhibits many genetic differences (Gross, 1998) due to gene selection and domestication. Farmed salmon can reproduce in natural waters (Carr *et al*, 1997) and outside their native range (Volpe *et al*, 2000). Selected for high fecundity and high growth, they may be more successful, but on the other hand, they are not used to prey catching and predator avoidance. Finally, escapes may spread parasites and diseases (Beveridge and Phillips, 1993) in a larger area than when stocked in cages. Damages from escapees are poorly quantified but establishment of self-sustaining introduced strains or the alteration of the indigenous gene pools is one of the most damaging environmental consequences of aquaculture (Arthington and Blühdorn, 1997). In any case, escapes constitute a direct financial loss for the farmer and may lead to excess of food dispatched.

1.3.4. Predators

Cage structures concentrate fish and waste, release escapees and congregate wild fish through their FADs (Fish Aggregation Devices) effect (Beveridge, 1984b). This food availability attracts various predators and opportunistic species. Mainly 7 species of predators cause problems in Scotland: Harbour seals, Grey seals, Shags, Herons, Cormorants, Gulls and Otters (Quick *et al*, 2002). Predation on stock causes direct lost through mortality or down-grading but also indirect from stress. Moreover, rearing equipments can be damaged by seals and farmers need to invest in protection devices such as seal scarers (52 % of sites) and top nets (90% of sites). Rueggeberg and Booth (1989) estimated 1.5% of total fish stock were lost through predation in British Columbia, where 60% of the farms had predators problems. Ross (1988) estimated that predator related losses in 1987, in Scotland, were £1.4-4.8 million but predation is not a major source of insurance claim (Kennedy, 1994). Predators are also pathogen vectors and some are intermediate host in the life cycle of parasites (e.g. *Diplostomum*, eye fluke, hosted by fish eating birds). The effects on the environment from community displacement (Carss, 1990), change in food web, spread of disease and effects of protection devices on non-target species are poorly quantified.

1.3.5. Chemical wastes

In-feed treatments are a recent alternative to bath treatments for different therapies but releases still occur in the form of uneaten food, fecal or excretory material. Most pesticides used in aquaculture are adopted from the agriculture industry, their effect in the marine ecosystem poorly investigated but their use is strongly regulated. Active molecules and “inert” ingredient enter the water column, may accumulate on sediment through feces and act on non-target species, commercially and ecologically important, particularly crustaceans and early life stages. Between 60% and 85% of the drug can be excreted unchanged (Samuelsen, 1994; Weston, 1996) and persist in the sediments for several months (Weston, 1996). Resistance in target pathogens (*A. salmonicida*) and sediment bacteria has been shown (Husevåg *et al*, 1991; Nygaar *et al*, 1992; Barnes *et al*, 1994; Hawkins *et al.*, 1997). Finally, organisms can accumulate antibiotics in their tissues to levels which would be considered unacceptable for human consumption (Capone *et al*, 1996). However, the development of effective vaccines has greatly reduced reliance on antimicrobial compounds. In Norway, in 1999, the quantity used fell to 1% of their 1987 value despite the increase in salmon production.

Other chemical are also used such as copper-based anti-fouling. Copper gradually leaches in seawater and can be detected in sediment at low concentration.

1.3.6. Water quality variation

Lochs are estuaries, that is to say partially enclosed coastal region where freshwater from rivers meet and mixes with sea water. In river water, the relative proportion of various constituent is different than in seawater (minerals, toxic metal, solid matters,…) while the sea water wedge moves back and forth with tide. Therefore, water quality parameters fluctuate dramatically in a place from time to time, particularly salinity and pH. Those fluctuations act as environmental stimuli causing stress. Moreover salmons, being osmoregulators, keep the salt concentration of their body fluid constant which has a metabolic cost. If tidal movement and flushing rate are too strong, they may cause physical damage to cages or cage distortion resulting in management difficulties and physical abrasion of fish. Varying FCR, growth and disease sensitivity are inherent to cage production systems.

1.4. Legislation and perspectives

1.4.1. Current legislation overview

Various regulations and agencies are involved in marine fish farm development, mainly:

- The Crown Estate Commissioners (CEC) delivers lease.
- The Scottish Executive Development Department (SEDD) deliver permit to ensure developments do not present hazards to navigation, etc.
- SEPA deliver consent to discharge for any discharge from a marine fish farm.
- The Scottish Natural Heritage (NHS) has the statuatory responsibility to protect and enhance the natural heritage.
- The Scottish Executive Rural Affairs Department (SERAD) ensure compliance with the Disease of Fish Acts and related EC fish health directives and issue national guidance on marine fish farming.
- The Health and Safety Executive (HSE) ensure compliance with Health and Safety legislation.

Since 1985, The European Community has adopted the Environmental Impact Assessment (EIA) process as a prerequisite to develop or extent an aquaculture site. In Scotland, an EIA is required for each project involving a biomass in excess of 100 T or located in a sensitive area. The aim is to protect consumer, aquatic life, industrial and other stakeholders, but also aquaculturists since a functioning ecosystem is the resource base on which the salmon farming industry ultimately depends (Folke and Jansson, 1992).

On site scientific measurements are conducted and a range of data collected (hydrographic, bathymetric, physico-chemical) are analyzed by experts to estimate the present state of the water body and its environmental capacity. This capacity is based on Environmental Quality Standards (EQS) set by the Scottish Environmental Protection Agency (SEPA). They are operational standards; threshold concentration of individual substances defined from scientific research, chemical risk assessment and field validation. The difference between the present state and the assimilative capacity of the water body may leave an available gap which can be sustainably filled by the farm effluent controlled through maximum biomass and consent to discharge. Using the same principle, SEPA also work with Sediment Quality Criteria (SQC) and Aesthetic Quality Standard (AQS) (Stead & Laird, 2002). Once running, monitoring is required at defined frequency and methodology to check the reality of predictions and react in consequence.

Scottish Quality Salmon initiated a national treatment strategy, primarily for sea-lice infection control, from which several coastal area have been designated to establish an Area Management Agreement (AMA) among farmers and other local interests. Common sea-lice treatment strategy, synchronized harvesting and fallowing routines are encouraged and necessary for efficiency.

1.4.2. Perspectives

Carrying capacity uncertainty

Sustainability and its limit set by the carrying or assimilative capacity of the environment is recognized as a primordial principle by producers association (Scottish Quality Salmon) and regulatory bodies, particularly SNH and SEPA. Indeed, the primary objective of the Water Framework Directive is to promote and safeguards good ecological status of Scotland`s water resources. However, scientific uncertainties still remain on the impact of finfish industry on the overall environment (SNH, 2002) and the definition of carrying capacity is still under development. SEPA has identified the need to develop more robust predictive tools and to address the risk of combined effects of several fish farms. SQS recognizes those deficiencies and welcome the initiative to objectively understand Scotland`s marine carrying capacity.

Expansion

Therefore, this common agreement is operationally uncertain and the industry expansion is unclear. The Scottish aquaculture association has addressed, among other considerations, the following development plan over the next 5-8 years:

- SA being positioned nationally and internationally as a commercially competitive core industry delivering products reputed for their quality and sustainability.
- Employment increasing from 7,000 to 9,000 permanent and skilled
- Export value increasing from £200m to £400m pa

However, SEPA consider that in some areas production levels may now be exerting a significant polluting load and the present rate of extension can not be sustained with its present practices. SEPA and SNH favour a strategy which conserves the superior product quality of Scottish salmon, its reputation to come from a pristine environment and to sustain the current socio-economic and health benefits of the industry. Focus should be given to value added and specialist niche retail markets. SNH goes further and would like to see the industry take steps to limit major expansion, minimize the development of new sites and increase environmental management of existing sites. Moreover, there is an agreement about the need to relocate some farm: Those located close to the mouth of watercourses important for migrating salmonids and those where monitoring results indicate an unacceptable impact while biomass reduction is not viable.

New location and diversification

For environmental conservation aims, the strategic frameworks for aquaculture consider 2 main alternatives for farm siting: offshore and landbased. Those siting alternatives will also be more and more wanted for production safety. We are going through a period of “global warming” with more varied and unpredictable weather patterns. This will probably increase the frequency of large scale environmental loss with consequences on insurance cost and coverage.

Even for farms free of previous large loss, it is probable that insurer will consider that the "probability of that farm to be affected by a natural disaster is merely increasing each year" (Aquaculture Risk (Management) Ltd., 2001). Thanks to technological advances in cage and mooring, off-shore siting offers deeper water, greater flushing, greater distance from salmonids migration routes and reduced visual and landscape impacts. However, such site are prone to strong weather which may cause equipment damage, greater risk of escapes and no access to sites for several days at a time. Moreover, in such conditions, fish are unable to maintain position within the pen and can be severely damaged by being driven against nets (Richards, 2002).

Land based systems offer an easier way to control environmental interactions. SNH support exploring location of fish farms on land with satisfactory landscape assessment and waste treatment, but SEPA notes that tank farms techniques are not likely to be economic for salmon production at present market prices. Diversification could provide opportunities for increasing output and maintaining growth. Among a full range of research required, regulatory bodies have identified the need to develop remediation systems for aquaculture by-products and to conduct "a study to compare the real costs of salmon farming onshore and those of farming in the sea, including factoring in all environmental costs."

1.5. Methodology

The ability to face up to those problems will determine the evolution of the Scottish Salmon Industry. The aim of this study is to compare two alternative rearing systems: off-shore and recirculating. The high capital cost of the recirculating system may be off-set by its benefits in term of growth, survival, product quality, risk and reduced environmental interactions. Two models have been developed based on the same scale of 1000 t Atlantic salmon production per year, from an 80 g smolt to a whole salmon supplied to processing center. This scale has been selected since it is an average cage site size nowadays and offers potential economies of scale for the recirculating system. Design and costing is based on bibliography review, experience of *Pisces-Engineering Ltd., Stirling Aquaculture consultancy* and professional contacts among the Scottish Salmon Industry. This gave us the material to compare the financial performance, profitability and cash flow, of both models. Then, risks, environmental impact and sensitivity analysis are addressed as major factors for an investment decision and strategic choices.

2. Technical models for 1,000 t per year Atlantic salmon production

2.1. Cage farm model

2.1.1. Rearing system

Growth cycle and technical data

The growth cycle is dependent upon the seasonal water temperature variations. Typical temperatures from the Mid West Coast of Scotland are provided in table 2.1 (Turrel, 1998). The ideal cycle (every day feeding) gives a 4.8 kg Atlantic salmon from a 80 g smolt after 16 months of rearing as shown in table 2.1. Next to this "spring" cycle, a fallowing period of 8 weeks is considered followed by an autumn cycle which gives in the same period a 4.4 kg salmon. Over the cycles, the mean feed rate (FR) is 1.1 % bw/day and the mean specific growth rate (SGR) 0.84 %/day. The food conversion rate assumed (FCR) is 1.3, as a typical efficiency in cage system.

Table 2.1: Temperature, individual weight, food consumption and mortalities over the cage cycle

Month N°	Water T(°C)	Mean Ind. weight (g)	Food (g/ind)	Mortality (%)
March	7	80	0	2
April	7.5	131	74	1
May	9	230	131	1
June	10	352	160	1
July	12.5	536	242	1
August	14	785	327	1
September	12	1040	331	0.5
October	10.5	1340	391	0.5
November	8	1615	356	0.5
December	7	1892	361	0.5
January	6	2102	270	0.5
February	7	2388	363	0.5
March	7	2742	446	1
April	7.5	3133	528	0.5
May	9	3614	628	0.5
June	10	4150	699	0.5
July	12.5	4786	832	0.5

Based on Trouw`s recommended Feed Rate for their AminoBalance™ range of diet (Stead & Laird, 2002)

The mortality assumed is 10 % as discussed (p.3). This mortality being forecasted, more smolts are stocked and the targeted production is realized.

Production cycle

Traditional square cage sites may use a "swim-through" strategy where fish from each cage are moved every 3 weeks or so to allow for net drying and avoid anti-fouling use. Moreover, several batches, from same origin, may be used to spread production and management (R. Hawkins, pers. com.). This management needs about 1 empty cage out of 5. The proposed strategy is different due to handling difficulties on circular cages. The number of fish required to give the targeted production per cage is initially stocked, taking into account likely mortalities, then fish are not transferred. This gives a much less cost-effective use of space (low density at early life stage) but decreases need for labour and handling as associated risk (Beveridge, 1984b). Single year class rearing is recommended by the *Shetland Salmon Farmers` Association* (2000) to avoid cross infection risks as an "all in, all out" approach to allow for fallow periods; this is largely practiced among the industry. As a consequence, the biomass on the model site ranges from 0 to 1333 t in order to have a mean production of 1000 t a year with 326,000 smolts stocked.

Cage sizing

In the exposed conditions of the model, circular cages are required for resistance to strong weather. They also offer several advantages such as better water transfer, greater effective stocking capacity and little maintenance. Cages used are from the "ORCA" range built by *Pisces Engineering.* They provide reliability and easy management in exposed areas with the following characteristics:

- Galvanized steel stanchions
- Virgin black, UV stable, polyethylene plastics.
- 3 rings, 400mm diameter, 96 mm circumference

Two sizes of knotless nets (9.5mm and 22mm, 12 m depth) will be used with regards to fish size in order to maximize water exchange. The net life span, 6 years in traditional conditions, is reduced for large cage in exposed sites therefore we considered depreciation on 4 years.

The volume installed is 70,440 m³ with 8 cages of 96 m circumference and 12 m depth (table 2.2), for a peak density of 19 kg/m³. Higher water flow allows for higher density than conventionally done nowadays by the industry. Two additional cages are installed to allow for grading, treatment or damage.

Table 2.2: Cages sizing

Peak biomass	(t)	1,333
Density targeted	(kg/m^3)	20
Volume required	(m^3)	666,50
Volume unit	(m^3)	8,805
Unit used	(unit)	8
Volume realized	(m^3)	70,440
Density realized	(kg/m^3)	18.9
Individual cost (Pen, nets, mooring)	(£)	58,500

2.1.2. Land based requirement

The total surface of the land-based station is about 1,050 m² (£20/m²) which includes:

- 100 m² office and accommodation: Prefabricated building made of steel with insulated steel laminated panels on conventional foundation.
- 250 m² workshop and stocking: farm building
- 220 m² parking: graded gravel on compacted soil.
- 560 m² concrete floor for self-net cleaning.
- 100 m heavy capacity road, 4m wide, covered with bitumen.

2.2. Recirculating Aquaculture System (RAS)

2.2.1. Rearing system

Growth cycle and technical data

The growth cycle is based on a constant temperature of 16ºC which provides an optimum FR (1.5 % bw/day) and SGR (1.23 %) over all the cycle. The FCR assumed, 1.2, is 0.1 better than in the cage model due to greater ingestion (no wind and flow to export pellet out of the cage) and conversion (constant flow, reduced environmental stress). Therefore, Atlantic salmon mean weight reaches 4.6 kg from an 80 g smolt after 11 months of rearing, as shown in table 2.3. The mortality assumed is also reduced to 5% due to the absence of predators and the reduction of stress (environmental variations) and infection. The food protein contents ranges from 45% to 40% at harvest.

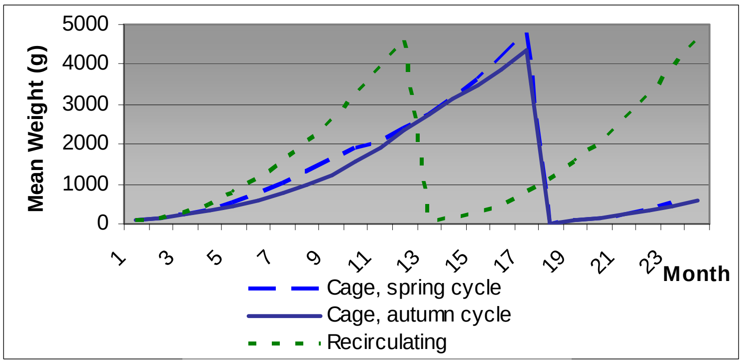
Table 2.3: Individual weight, food consumption and mortalities over the RAS cycle

Month N°	Ind. Weight (g)	Food (g/ind)	Mortality (%)
0	80	0	1
1	158.6	107	0.5
2	297.2	162	0.5
3	500.6	254	0.5
4	793.9	355	0.5
5	1,149.2	430	0.5
6	1,560.5	496	0.5
7	2,048.5	588	0.5
8	2,588.8	651	0.5
9	3,215.4	754	0.5
10	3,924.7	857	0.5
11	4,664.8	857	0.5

Based on Trouw`s recommended Feed Rate for their AminoBalance™ range of diet (Stead & Laird, 2002)

Cycle of individual mean weight is much quicker for the RAS than for the cage as shown in figure 2.1. However, each model is sized to produce 1,000 t a year.

Figure 2.1: Cycles of mean weight in cage and RAS models



Production management and systems presentation

The farm design is based on a trade-off between equipment sizing and handling requirement with a total of 5 individual recirculating systems:

- 1 system for the first 2 months, stocked 4 times a year (Pre-grow out system).
- 3 systems for 9 months of growth-out, given 4 batches a year (Grow out systems)
- 1 system for starvation and sales management (Commercialization system).

This design gives an efficient use of space together with a biomass relatively constant in each system, as shown in table 2.4. The nil biomass in system P is theoretical, in practice this quantity should not be maintained more than a week. The biomass in system G ranges from 19 t (32 t end of first month) to 199 t.

Fish are progressively harvested (20 t a week) from system G during their 9th, 10th and 11th month on the farm (table 2.4), from which they will be transferred to the system for commercialization (system C). In this last system, fish will be starved before slaughter for about 10 days and will not grow. Sales will be easily managed and regularized over the weeks; system C is sized for 40 t biomass to give flexibility. Predicted mean weights at sales and related volume are addressed in table 2.5.

Table 2.4: Biomass cycle in Pre grow-out and Grow-out systems

Month	System P	System G			TOTAL
		1	2	3	
Jan	0	32 d	199 b	98 c	329
Feb	10.2 a	50 d	176 b	128 c	364
Mar	19.0 a	73 d	114 b	161 c	367
Apr	0	98 d	32 a	199 c	329
May	10.2 b	128 d	50 a	176 c	364
Jun	19.0 b	161 d	73 a	114 c	367
Jul	0	199 d	98 a	32 b	329
Aug	10.2 c	176 d	128 a	50 b	364
Sep	19.0 c	114 d	161 a	73 b	367
Oct	0	32 c	199 a	98 b	329
Nov	10.2 d	50 c	176 a	128 b	364
Dec	19.0 d	73 c	114 a	161 b	367

Letters in superscript represent the batch
Underlined biomasses are partially harvested

Table 2.5: Harvest from system G and sales weight

Month No	Mean Weight (g)	Quantity	Biomass (t)	% Weight
9	3,215	49,248	158.4	15.8
10	3,924	98,004	384.6	38.5
11	4,664	98,004	457.2	45.7
TOTAL	4,150	245,257	1,000	100

The total biomass on the farm ranges from 329 t to 367 t at any time (excluding sales system, maximum 40 t). The farm produces 1,000 t a year with 258,900 smolts of 80g stocked.

Tanks sizing

The density in RAS is not a limiting factor as soon as appropriate design is provided. The density targeted, 50 kg/m^3 is slightly more than twice as high as in cages, but still lower than the maximum density approved by the animal welfare associations (Bob Bawden, pers. com.). The farm is equipped with glassteel tanks due to the large size required, from *Permastore*. Size and quantity are addressed in table 2.6. Raceways offer easier management for partial harvest and isolation; they are made of concrete. The commercialization system is not discussed here; its cost estimation is £40,000 (excluding pre-establishment costs).

Table 2.6: Tanks sizing

		System P	System G	System C
Peak biomass	(t)	19	199	60
Density targeted	(kg/m^3)	50	50	50
Volume required	(m^3)	381	3,979	800
Volume unit	(m^3)	236	1,287	800
Unit realized	(unit)	2	5	2
Volume realized	(m^3)	471	6,437	400
Density realized	(kg/m^3)	40	31	50
Number of systems	(unit)	1	3	1
Total number of tanks	(unit)	2	15	2
Individual cost installed	(£)	17,000	30,000	-
Unit type		Tank	Tank	Raceway
Diameter	(m)	10	20	L = 24.2 W = 6
Depth	(m)	3	4.1	3

2.2.2. New water input for Nitrate-Nitrogen control

The recirculation system design is a conventional ring system where each process is controlled by the preceding process. It is described and sized in the next sections with a summary in Appendix B.

The system is not equipped with a denitrification process; Nitrate-Nitrogen (NO_3) concentration from nitrification process is controlled by new water intake. The method used is taken from Losordo and Westers (1994) and is based on the nitrate mass balance equation under steady-state conditions. The flow rate selected is much greater than the minimum required for systems and biomass safety (Table 2.7) with a daily incoming water of 6,210 m^3/day (72 l/sec). The intake station will be made of 2 pipes of 300 mm diameter and 200 m long. The seawater pumped is firstly stocked in a collection pit to avoid drawing up air in the system. While a pipe is used, freshwater flows through the other one to the sea in order to kill and detach fouling organisms. Freshwater requirement is discussed later as a cooling power.

Table 2.7: Flow rate requirement and selection

		Grow-out	Pre Grow-out
Peak biomass	(t)	199	19
Feed Rate	(% bw/day)	0.8	2.25
Food dispatched (FA)	(kg/day)	1,592	430
Feed protein content (PC)	(%)	40	45
TAN produced (P_{TAN}) *	(kg/day)	64.95	19.73
Minimal Flow rate	(m^3/day)	216.5	65.8
Selected Flow rate	**(m^3/day)**	**2,000**	**210**
System volume	(m^3)	7,500	775
Percentage recycling	(%/day)	73	73

***** $P_{TAN} = (FA*0.102PC)$

2.2.3. Solid waste removal

An efficient solid removal system is a key factor of success since solids have several negative impacts: direct damage of fish gills (Chapman *et al*, 1987), mechanical clogging of biofilters, ammonia production by mineralization and oxygen consumption. Therefore, removal should be as quick as possible and particle degradation minimized.

Solid removal system is based on the diameter of particles to remove from the system. Most of the faeces and uneaten food keep a size over 50 μm, are self-cleaned by an appropriate water flow and easily filtered out. In established system equipped for removal of such particles, remaining solids are predominantly smaller than 20 μm in diameter (48% to 72% volume; Harman, 1978; Chen *et al*, 1993). Due to the “gap” of solid distribution and the high cost for fine particles extraction, treatment will concentrate on particles greater than 40 μm and inferior to 20 μm with respectively drumfilters (Table 2.8) and foam fractionation.

Drumfilter

Table 2.8: Drumfilter requirement

		Grow-out	Pre Grow-out
Flow rate in tanks	(l/sec)	1,110	351
Individual capacity	(l/sec)	700	180
Quantity required/system	(unit)	2	2
Individual cost installed	(£)	60,000	24,500

Foam fractionation

Foam fractionation mainly refers to dissolved solids removal but suspended solids are simultaneously removed in this process (Chen, 1991). The unit, in a large scale aquaculture system, is typically a tank where bubbles generated at the bottom rise upwards, providing an attachment substrate for dissolved but also fine suspended solids smaller than 30 µm (Chen, 1991). The foam formed is removed at the top of the water body and stocked in a 30 m^3 tank. The foam fractionation unit will treat 10% of the flow to minimize head loss and foam production, its characteristics are specified in table 2.9. The submerged biofilter also filters fine particles.

Table 2.9: Foam-fractionators description

		Grow-out	Pre Grow-out
Flow rate treated	(l/sec)	111	35
Tank diameter	(m)	3	1.5
Cost installed	(£)	5,500	2,500

2.2.4. Biofilters Design

Biofilters are sized for the maximum biomass reared in the system. The method used is given by Wheaton *et al* (1994), results are addressed in table 2.10 and 2.11.

Table 2.10: TAN production and Specific Surface Area (SSA) required

		Grow-out	Pre Grow-out
TAN produced (AP)*	(kg/day)	48	13
TAN removed by the filter**	(g/m²/day)	0.182	
SSA required	(m²)	262,418	70,838

** Liao and Mayo, 1974, AP = 0.03*(Feed fed/day)*

*** Ammonia removal is 0.52 g/m2/ day at 16ºC; typical biofilter efficiency 35 %*

The biofilter is composed of two units to efficiently combine their characteristics. Water will firstly go through a fluidized bead-filter which is auto-cleaned but produces fine particles, then a submerged bead-filter will catch those fines but will need to be back-flushed.

Table 2.11: Biofilters configuration

		Grow-out		Pre Grow-out	
		Fluidized	**Submerged**	**Fluidized**	**Submerged**
SSA required	(%)	75	25	-	-
SSA required	(m^2)	196,813	65,604	53,128	17,709
Media SSA	(m^2/m^3)	900	150	-	-
Volume in tank	(%)	50	100	-	-
Effective media SSA	(m^2/m^3)	405	135	-	-
Volume required	(m^3)	488.4	488.4	131	131

The water flow rate in the RAS determines the number of pass through the biofilter, which must be adequate to ensure that the concentration of ammonia is kept below the level of toxicity for salmon. The equation takes into accounts the parameters addressed in table 2.12 to determine the minimal flow rate in the tanks.

Table 2.12: Determination of flow rates with regards to [TAN]

		Grow-out	Pre Grow-out
Biofilter efficiency	(%)	35	35
New water flow rate	(l/min)	1,390	146
New water [TAN]	(mg/l)	0	0
System [TAN]	(mg/l)	2	2
TAN produced	(mg/min)	45,107	13,698
Allowable [TAN]	(mg/l)	2.00	2.00
Flow rate (+10 %)	(l/min)	66,520	21,070
100 % renewed	(min)	98	22
Retention time (t_m) *	(min)	7.3	6.2

** Liao et al (1972): t_m = E/(9.8T-21.7) where E : efficiency (%) and T : temperature (ºC)*

Allowable TAN concentration (A_{TAN}) is calculated from the mole fraction (a) of unionized NH_3-N and the allowable NH_3-N concentration for salmon (0.025 mg/L).

$$A_{TAN} = A_{NH3\text{-}N}/a$$

The mole fraction of NH_3-N is the decimal equivalent concentration of NH_3-N compared to the whole of NH_4-N plus NH_3-N in the aqueous system. In our system, the temperature will be 16ºC, the salinity around 27 g/kg and the pH 7.5. While sea water pH is around 7.8, the biological treatment will slightly reduced it by H^+ formation from nitrification. We consider the highest proportion of unionized ammonia (pH 7.8, TºC 15) which gives a mole fraction of unionized NH_3-N of 0.01 (Khoo *et al*, 1977).

The flow rates determined provide an adequate ammonia presentation rate (from water flow) for adequate removal; the retention time is sufficient and the efficiency needed is under the predicted efficiency.

2.2.5. Turbidity removal: Ozonation

Being mainly a visual feeder, Atlantic salmon requires clear water to efficiently feed at high stocking density. Ozone is used in many aquaculture systems, including Atlantic salmon smolt hatchery, for color and turbidity removal with improvement up to 50% (William *et al.*, 1982; Sutterlin *et al*, 1984; Paller and Lewis, 1988). Ozone has several other effects on sea water quality in RAS, reviewed by Tango and Gagnon (2003): partial disinfection, inorganic and organic compounds oxididation (nitrite, NH_3, fine SS), reduced TSS accumulation reduction and removal improvement, nitrate level reduction and foam fractionation enhancement (Moe, 1989). However, ozone has toxic effects which have been reviewed by Rosenthal (1980) and other researchers. From naturally occurring bromide, bromate is formed which is toxic to fish, humans and biofilter bacteria. Other unwanted chemical byproducts may be formed and certain trace elements, particularly manganese, depleted (Spotte, 1970). However, if ozone is degassed and residual concentrations remain low, it can be safely used.

Tango and Gagnon do not address the quantity of ozone used to obtain published results. The use of 8g O_3/kg food/day is, from experience, safe in sea water. With a maximum food dispatched of 5882 kg/day, the maximum ozone requirement on the farm is 51.8 kg O_3/day (1.33 kg/h), including 10% margin. The monthly requirement varies for a total annual consumption of 11.4 t O_3. Ozone is very unstable and must be produced on site and readily used. The addressed quantity will be produced from pure oxygen by a 10 kW silent electrical discharge generator (£30,000) and distribute through 4 injectors (£3,000). Pure oxygen feeding usually costs less than air feeding (Wheaton, 1977) due to reduced energy consumption and no requirements for air drying. However, efficiency of this system remains low with only 9% of the O_2 transformed into O_3 and transferred in the water, 76% of the remaining O_2 passing into the water. Ozone will be injected in the foam fractionators to improve its efficiency and reduce risk for biofilter and fish. Ozone residual will be removed in the CO_2 packed column addressed later while the bromate level remains low due to the reduced use of ozone (10 % of the flow treated).

2.2.6. Oxygen supply

Oxygen requirement

In order to design an efficient O_2 supply system, the consumption of the different organisms of the system was considered: Fish, other water column organisms and biofilter. Table 2.13 addressed the value and formulas used for O_2 requirement determination.

Table 2.13: Oxygen consumption and oxygen level required in RAS

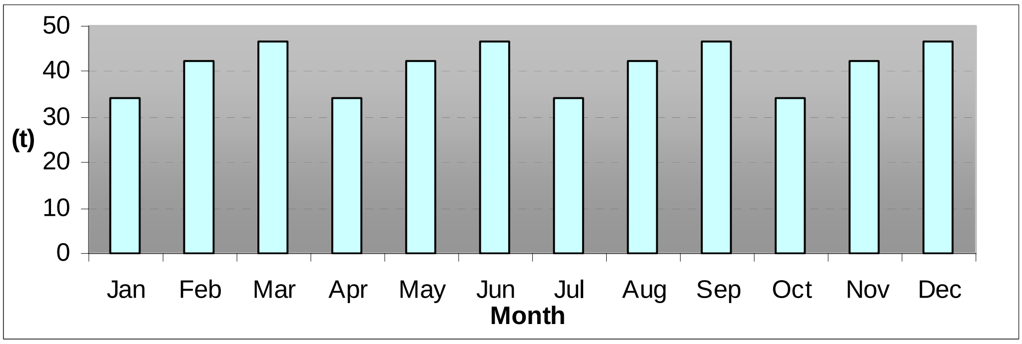
	Value/Formula	**Reference**
Salmon, mean weight < 1kg	$Q = 0.531W^{0.86}$ *	Tolkunova, 1973
Salmon, 1 kg, 16ºC	0.552 kg O_2/100kg/day	Liao, 1971
Salmon, mean weight > 1 kg	$Q = 0.148W^{0.84}$ *	Kazakov & Khalyapina, 1981
Salmon, mean weight > 1 kg, adapted for 16ºC rearing medium	$Q = 0.148W^{0.84} \times 1.26$	
COD	Ignored	
BOD_5	5.3 mg/L (1.06 mg/L/day)	Singh *et al*, 1998
Stochiometric requirement for ammonia conversion to nitrate	4.18 g O_2/g NH_3-N converted	Hochleimer, 1990
Total O_2 requirement of autotrophic bacteria (Stochiometric+ respiration)	4.57 g O_2/g TAN removed	Losordo and Hobbs, 1999
O_2 solubility in seawater (27 ppt, 16ºC)	8.5 mg/L	Benson and Krause, 1984
Minimal [O_2] in tank	5 mg/L	Pillay, 1990
Minimal [O_2] in biofilter	4.5 mg/L	

** Q (mg/L); W (g)*

The oxygen consumption of the biomass for salmon weighing 1 kg is 26% higher from Liao than from Tolkunova; this is due to the unusually high temperature employed used by Liao. For adult salmon, the consumption rate calculated from Kazakov & Khalyapina`s equation is increased by 26% to consider the high rearing temperature of the recycling system. The water column is colonized by autotrophic and heterotrophic bacteria which respire, realize passive nitrification, denitrification and decompose organic matter. BOD value was found to be constant in mature recirculating trials involving different types of biofilter, solid removal and feeding rate for hybrid striped bass (60 kg/m³) (Singh *et al*). Other sources of O_2 consumption are addressed in table 2.13.

Oxygen input (Figure 2.2) is determined from a monthly balance between O_2 availability and requirements, varying with fish size. The daily requirement of oxygen to produce ozone is under the global oxygen requirement and so, ozone production from oxygen does not add a significant oxygen requirement (oxygen untransformed by the O_3 generator is used for respiration).

Figure 2.2: Monthly oxygen requirement



From the oxygen requirement values, the quantity to inject is obtained by considering a transfer efficiency of 85% and adding a safety factor of 10 %. An average of 0.4 kg O_2/kg food delivered is injected over the cycle. The monthly requirement varies between 34.1 t and 46.5 t for an annual consumption of 490.7 t or 343,400 m³ (1.429 kg/m³). A price of £0.11/kg gives an annual cost of £53,979 (£148/day, £0.054/kg). This high consumption is due to recirculation together with large scale intensive production and high temperature.

Oxygen input system

The system in place must be totally secured. The best option is to use liquid oxygen technology which does not require an external power supply, is relatively simple, efficient and cost-effective when purchased in bulk quantities. The site needs to be located near a reliable supplier. A liquid oxygen system consists of a storage tank for the liquid gas, vaporizers to turn liquid oxygen to gas, and supply lines to the fish tanks. Stored in a tank in the liquid form, 1 liter of tank volume stores the equivalent of 0.81 m^3 O_2 (1bar, 15°C). In order to have a 3 weeks autonomy in period of peak consumption, 22,762 m^3 of O_2 needs to be stored. This is equivalent to a liquid oxygen tank of 28.1 m^3 which is rented for £25,000 /y with control equipment. The whole system installation cost is £25,000. Oxygen will be injected only in tanks.

2.2.7. pH and CO_2 control

pH and CO_2 levels are two important factors which may become limiting at high density if not controlled. pH variation induces fish stress, can increases the toxicity of other compounds and may reduce nitrifying bacteria activity (optimal range: 7.0 to 8.0 for nitrosomonas and 7.5 to 8.5 for nitrobacter, Grady and Lim, 1980). pH decreases as CO_2 levels increase while the drop in pH is dependant upon alkalinity (Total Carbonate Carbon) and temperature. In order to reduce pH variation and its negative effects, alkalinity should be kept at a relatively high level even if it increases CO_2 to remove, since alkalinity is a carbonate carbon reservoir. However, CO_2 is a very soluble gas and relatively simple to remove (Piedrahita & Grace, 1991). Needs of pH control could be defined primarily from incoming alkalinity and that produced by the system. However, a mass balance of CO_2 production (0.28 kg/kg of feed, Colt, 1986) and extraction by the packed degassing column is also required; this is dependant upon column design: Gas/Liquid ratio, water depth and alkalinity. Piedrahita and Grace (1991) studied the efficiency of packed columns in various conditions and concluded that the conventional equations for packed column aerators overestimate the amount of CO_2 removed, and that packed columns for pure oxygen may not offer sufficient opportunity for CO_2 to be removed, due to their low Gas/Liquid ratio (below 1). Practically, pH can be adjusted to requirements with a pH control pump delivering, e.g. diluted magnesium carbonate or white coral sand in the inflow stocking tank (J. Orbell, *Marine Harvest*, Lochailort Smolt Unit, pers. com.). This pump can be connected to a pH meter to automatically deliver and maintain a theoretically constant pH. However, pH reading from electrodes may be false and can lead to fatal consequences. A simpler method which is used in commercial RAS is to deliver the required substance through an automatic feeding system and adjust quantity with respect to value read from pH paper. This system is a little time consuming but finally more reliable if consistently managed. CO_2 control will be achieved by a specifically built packed column having a depth of about 1.5 m (removal efficiency increases slowly with greater depth) and a G/L ratio above 5. A fan, which is ideal for continuous duty, simple, clean and oil free will deliver high quantity of air at low pressure. The power required is 2 kW with 85% efficiency.

Precise system design is not developed in this preliminary study due to sizing uncertainty compared to the relative low cost of those systems. We considered a total price of £1,500 per pH and CO_2 control system while the fan electricity consumption is taken into account in the operating costs.

2.2.8. Pump system for water circulation

Conventional centrifugal pumps are used; they are simple, relatively cheap and particularly efficient for medium head loss use. For continuous duty, electric power provides low maintenance and cheaper operating cost. Pump selection and prices are based on *Grundfos* range (three phase, 50 Hz, centrifugal**)**, even if it may not be the most cost-effective option due to their usual capacity for high head loss from conception, which is not required here. They are sized for an exit pressure of 1 bar and appropriate for salt water use (Table 2.14).

Table 2.14: Pump Park required on RAS for water circulation

		New water	**System P**	**System G**
Maximum flow rate	(m³/h)	259	1,264	3,991
Head loss	(m)	12	4	4
Flow rate of pump selected	(m³/h)	260	220	500
Number of pump per system	(unit)	1	6	8
Motor power	(kW)	11	5.5	22
Individual price	(£)	20,00	2,025	10,630

2.2.9. Waste management

The organic wastes from the system are wet with sea water which makes them not readily suitable for organic or traditional valorization. In order to get rid of this quantity of waste and due to the actual lack of other economical options, the strategy proposed is to sterilize wastes and to discharge it off-shore in a high dispersion area.

Quantification

An estimation of faeces ranging from 25 to 30% of the feed consumed is well accepted for salmonid (Westers, 1989; Iwama, 1991). Uneaten food from dry food in a cage system represents 5-15% of the diet (Trevor Telfer, pers. com.). In a tank system that is more easily controlled and quieter, we assume 5% of the food dispatched will be uneaten, including 2% of dust. Moreover, bacterial populations growing in the water column, on the tank walls, in pipes and in the biofilter (biofloc) increase this load by 5% of food dispatched. With a wet:dry ratio of

10:1 and a 1236 t of food dispatched over the cycle, a total of 4946 t of wet waste will be produced annually (faeces: 3,710 t, uneaten food: 371 t, dust: 247 t, biofloc: 618 t), a mean of 570 kg per hour.

Options

Several options can be used to stabilize and reduce sludge volume. Biological degradation could be an effective option. Bio-logics provides *Ultra Bio-MD Manure Degrader* for starch, cellulose, protein, fat and oil digestion using non pathogenic live bacterial strains and enzymes. This product is said to be effective for wet salt application but trials are required. With 2 to 10 kg of this product needed to treat 100 tons of sludge, 247.3 t of biological digester for a cost of £494,600 (£2.0/kg) is required in our case.

Biogas production from anaerobic digester (35ºC) may be possible for marine waste (Colgate, 2001). This process produces methane and reduces pathogen load but the design is complex and usually developed for freshwater organic waste such as trout farms` effluents.

Vermicompostage is actually being investigated (Tom Losordo, Rhonda, pers. com.) and may provide effective treatment in a few years` time.

Treatment by integrated crops, such as plants in lagoons or sea-weed cultivation, has potential. A trial on a trout farm proved 93% solids removal, 58% BOD reduction, 74% ammonia removal and 50% phosphorus decline (Colgate, 2001).

Sterilization

The specific heat (c) of liquid organic effluent is about 0.70 kcal/kg/°C and the aim is to heat 13.68 T (m) of effluent per day from 10°C to 80°C ($\Delta T = 70°C$). Therefore, the daily energy required is 670,320 kcal, 779.8 kWh.

$$\text{Energy input (kcal)} = \Delta T * c * m$$

Natural gas costs 1.01 p/kWh, the energetic cost of this treatment is £7.88/day, £2,876 per year. In order to treat the peak solid waste produced in a day (14.86 t), the power required is 38.8 kW working 24h a day, including a safety margin of 10%.

The cost of the sterilization unit installed is estimated at £15,000. To regulate the flow entering the unit and leaving the site, effluents are held in storage tanks having a capacity of about 4 days (40 m³), which have a cost of £1,500 once installed. In order to pump the effluent to the sterilization unit and to the sea, we need two effluent pumps having a maximum flow rate of 15 l/min, each requiring a power of 1.5 kW. Pre and post-stocking tanks are both equipped with water level devices and systems to switch pumps on and off, which are costless.

Waste will be discharged through a 500 m pipe made of 300 mm diameter concrete rings and a tidal opening system.

2.2.10. Buildings and surface

Due to the large rearing surface, a polytunnel is not cost-effective. Each tank will be covered by individual domes, lightproof, with 10 cm insulation (£14,000 for 20 m diameter tank). Equipped with light, photoperiod can be efficiently controlled. A ventilation system will give opportunity to avoid or to use the heat produced in the technical building depending on needs. O_2 tanks, biofilters, waste, food, foam and fuel storage tanks will be left outside. Other technical devices of RAS (drumfilters, pumps, foam fractionators…) will be protected in an insulated prefabricated building. The surface needed is 1,200 m² to include:

- Waste sterilization unit
- Boiler, cooler and ventilation systems
- New water pumping and heating system
- Offices

- Workshop
- Feeding system

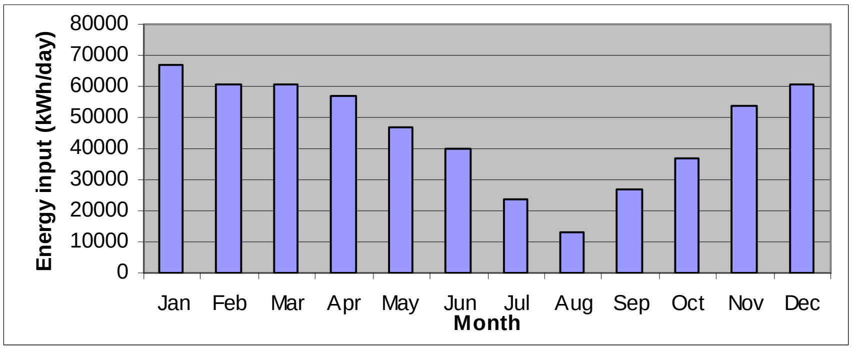
With a parking area of 230m² (21m*11m) and extra surface for external devices, the surface area of land required is about 13,000 m².

2.2.11. Energy

Natural gas requirement

Although tanks are covered, water has to be heated to reach 16°C all year round. Every day, 6,210 m³ of sea water is imported. With a specific heat of 0.93 kcal/kg ºC and the seasonal temperature variation, the daily energy input varies with months, as shown in figure 2.3.

Figure 2.3: Daily energy input required to heat incoming water to RAS rearing temperature



Marine Harvest Lochailort Smolt Unit needs to heat the water to 16°C only about 2 weeks a year for their 650 m^3, 90 % recycling system. From the experience of *Pisces Engineering*, a 300 kW boiler working 5h a day is sufficient thanks to the addressed air management and heat gain from biomass metabolism. This is high compared to *Marine Harvest* cited system but the RAS model design is more energy effective (lower heat gain) and the recirculating rate higher. The boiler must provide an extra 40 kW for waste treatment. This boiler provides a total of 2460 kWh a day for a cost of £9,069 a year (1.01 p/kWh) (Department of Trade & Industry, March 2002).

During summer months, water requires cooling even if dome coverages are removed. The *Marine Harvest* cited system use a 100 kW cooler for the main part of the year which is the main energy cost (J. Orbell, pers. com.). The cooling power required is estimated at 1000 kWh per day for the RAS addressed. A cost-effective solution is the use of a freshwater bow hole. A 500 L/min spring with 10ºC water provides safely the cooling power required: with 3ºC of heat exchange, the cooling power is 1250 kWh in 12h. Good water quality is not required for this purpose and for pipe intake cleaning but may be interesting for site cleaning and ice production in process plants. The cost for the bow-hole exploitation is £14,000.

Electricity requirement

With 349.6 kW of electric devices installed working all time (Table 2.15), the annual electricity consumption is slightly over 3,062 MWh, giving an electricity price of 3.06 p/kWh (Department of Trade & Industry, March 2002). The provisional electricity bill is £93,712 per year.

Table 2.15: Electric devices installed and daily electricity consumption

	Power (kW)	**Qtty (unit)**	**Power installed (kW)**	**Power consumption (kWh/day)**
Pump New water	8	1	8	192
Pump water flow (P)	22	8	176	4,224
Pump water flow (G)	5.5	6	33	792
Drumfilters (700 L/sec)	8.6	6	51.6	1,238
Drumfilters (180 L/sec)	3	2	6	144
Foam fractionation	1	4	4	96
Ozone generator	10	1	10	240
CO_2 degassing	2	1	2	48
Blower	10	4	40	960
Fan	2	4	8	192
Ventilation	1	6	6	144
Waste pump	1.5	2	3	72
Other	10	1	10	240
TOTAL			**357.6**	**8,582.4**

3. Management with emphasis on cost

3.1. Smolt supply

In Scotland, the cost of an 80 g smolt is 80 p on average. Quantities and costs required are addressed in table 3.1.

Table 3.1: Smolt requirement

		Cage model	RAS model
Quantity required	(unit/year)	244,500	258,900
Price	(£/year)	195,600	207,120
Biomass produced/smolt	(kg/unit)	4.09	3.86

Despite a greater mortality rate in cages, the quantity of smolts required is slightly reduced due to a greater mean weight at harvest. Supply by helicopter is the best alternative for a fairly exposed cage farm. Helicopter service can be rented (*e.g. PDG helicopter*) for £1,200 per day or £505 per hour with a capacity of 325 kg of smolt per lift. Road transportation is a better alternative for the land-based farm. A second hand 33 t, 13 m truck equipped with a crane and 28.8 m³ of fish transport tanks is required for the RAS. The transport density is 50 kg/m³ with oxygenation. Analysis is based on a supplier located 8 km away (5 miles) in both cases. Table 3.2 addresses the cost of smolt stocking with regards to transport methods.

Table 3.2: Cost of smolt supply management

		Cage model		RAS model
		Cycle	***Year***	***Year and cycle***
Capacity	(t live fish)	0.325		1.44
Biomass to stock	(t)	26	20	21
No of round trip	(unit)	80	62	14
Time for 1 round-trip & transfers	(h)	0.25		2.40
Total time	(h)	20	15.5	35
Cost vehicle*	(£)	£2,400 [1]		£28,850 [2]
Cost of fuel (80p/L)	(£)			73.6

[1] *Rental* [2] *Second hand purchase*

Fish transported by helicopter are taken directly to where cages are moored. For the RAS, the water will be progressively heated to 16ºC after smolt stocking with an adapted vacuum fish pump (40-100 g; £15,000) and a fish counting device (£30,000) to reduce stress and physical damage.

3.2. Food management

Food requirement varies between models in spite of the same production (1000 t/year) due to FCR of 1.3 and 1.2 in respectively cage and RAS. The mean cost of food used is £710/t delivered on site (£670/t ex-producer). Storage facility must maintain feed quality by avoiding humidity, heat, insects, rodents, fungi, dirt and other contaminants with a 3 weeks capacity (autonomy, used-by date). The cage farm needs a capacity of 167 t of food at the end of the cycle against a peak of 110 t for the land based farm (1t pellet = 1.6 m^3). The cage farm needs a feeding barge (e.g. *RH multifeeder AS),* designed to service in medium exposed site, equipped with pneumo feeder, silos (200 t), computer control and feed sensor (*AKVA smart*) for a total of £548,000. For the land based system, due to a mix of fish size on site, we consider 3 different types of food: first 2 months (cat. 1), months 3 to 6 (cat. 2) and months 7 to 11 (cat.3); the silos is sized with regards to maximum the requirement at anytime (Table 3.3). A land based computerized feeding system with silos costs £40,000 installed.

Table 3.3: Food storage management for RAS model

Food category	Max. quantity consumed / 3 weeks (t)	Volume installed (m^3)
1	7.8	15
2	35.5	60
3	50.9	85

For each system, staff must carry out visual observation of feeding behavior, as well as regular checking and maintenance of the automatic feeder.

3.3. Sorting, grading and weighting

For cages, transfer is not required but grilses need to be sorted and stock needs to be graded 6 to 12 months after stocking. With a well-boat and 2 staff, it takes about 4 hours per cage, a total of 32 hours per cycle (8 cages), this translates into a 3 day rental at £6,000 a day. A fish pump, a circular grader and 4 individual counters plugged on grader pipes, *Vaki*, (£47,000) are required for additional handling from the workboat.

For the RAS, the constant photoperiod and temperature together with the rapid growth should not induce this early maturation, aquatic light are used for that purpose in some cage system (R. Hawkins, pers. com.). However, a transfer from system P to system G (mean weight: 300 g, 19 t/cycle) is required during which fish from 2 tanks are sorted into 5 tanks. Another transfer is required from system G to the commercialization system (mean weight: 4.08 kg, 1000 t/cycle). A fish pump (300-800 g, a circular grader and 4 individual counters plugged on grader pipes (£47,000) are also required. The growth cycle takes into account 48 h of starvation before those transfers.

Even with a smart feeding system, stock needs to be sampled and weighed on a regular basis to monitor performance, manage stocks, ensure health and determine when harvesting should be carried out. Hand sample weighting, used in conjunction with mortalities estimation, gives an estimation of biomass with 15-25% accuracy (Petrell *et al.*, 1993), is stressful and labor intensive. The *AKVASensor Biomass Estimation System* based on a video capturing and sizing system can be moved from cage to cage or tank to tank and costs £75,000. Each system needs this item.

3.4. Water quality management

For the off-shore site, thanks to preliminary investigations on site suitability, no complete water quality monitoring and is required. Basic parameters (DO, Temperature, pH and salinity) are measured once a day or so with appropriate tools: temperature-oxygen meter with temperature, salinity and pressure compensation and pH reading (portable and submersible): £672; refractometer: £80 (R. Hawkins, pers. com.).

The RAS obviously needs much higher water quality control and alarms. Factors controlled and corresponding devices are addressed in table 3.4:

Table 3.4: Water quality monitoring system for RAS

Parameter	Device	Function	Localization	Qtty
Level	Water level	Alarm	Each tank	19
Flow	Flowmeter	Control, Alarm	Each tank	19
Temperature	Thermometer	Control	1 tank per system	5
Oxygen	Oxygen meter	Control, Alarm	Each tank	19
Ammonia	Test kit	Control	1 tank per system	5
CO_2	Test kit	Control	1 tank per system	5
Ozone	Test kit	Control, Alarm	System water sump	5
pH	pH paper		1 tank/system/day	

Each of these control devices are centralized on a “farm patrol” alarm panel with touch-screen technology, which costs £3,200 for 58 channels. The total cost is £32,000 which includes 500 m cables and 31 motor starters for pumps.

3.5. Disease and mortalities management

Monitoring of fish stock heath is essential and based on farmer ability to evaluate fish behavior and production data. In the cage system, behavior changes under the cycle of environmental conditions (day time, tidal, water quality) while observation may be compromised by net depth, waves and bad weather. On land, observation is easy all year long and behavioral change indicates a technical problem or an effective disease. Observation and production data (Biomass sensor, FCR) gives efficient disease monitoring, but the cage system requires specific equipment in order to treat a disease: 3 tarpaulins for bath treatment and oxygenation device (£7,000 each). Mortalities must be removed as frequently as is practical, particularly during summer months to avoid disease spread and to detect any new mortality. On cages, an air lift system is required (£12,000/cage) against simple nets in shallower tanks. The facilities for mortalities disposal are identical in both systems (ensiling plant involving maceration and preservation in formic acid), non significant for small quantities and ignored in this study. Large mortalities are disposed in both cases through local knackers**.**

3.6. Harvesting

Starvation before harvest is necessary to empty gut and firm the flesh before killing.
A well-boat is rented in the cage model and the truck owned is used for harvest in the RAS model. In both transportation systems, the density is 150 kg/m³ due to colder water and low health requirement. The land based farm should develop its own processing plant to take full advantage of its product's freshness and all year round supply in order to reach niche markets with premium prices. This processing plant would ideally be located on the same site, but we considered a distance of 5 km (3 miles) to the farm against 50 km (31 miles) for the cage farm.
In the RAS, the maximum quantity to harvest is 25 t a week which would required 6 journey (round trip) of 2.5 hours, including 2h for loading/unloading, a total of 15h a week if the process plant is not located on site. For the cage system, the all-out strategy induces the requirement of a well-boat for 58 days (10 h/day) at the end of the cycle (Table 3.5).

Table 3.5: Harvest management

		Cage model		RAS model
		Cycle	***Year***	***Year and cycle***
Capacity of transport system	(t live fish)	22.5		4.32
Biomass to harvest	(t)	1,333	1,000	1,000
No of round trip	(unit)	59	44	231
Speed	(km/h)	14.8		40.0
Time for 1 round-trip & transfers	(h)	9.8		2.5
Total time	(h)	578	434	580
Cost of vehicle	(£)	£290,000[1]	£220,000[1]	*£28,850* [2]
Cost of fuel (80p/L)	(£)			1,856

[1] *Rental: £5,000/day* [2] *Second hand purchase*

3.7. Maintenance

Cages, nets, moorings, but also protection devices, must be checked in situ for integrity and fouling level. This is best carried out by divers (using a farm boat) once a month. A complete check is also required after each storm. Surface inspection by staff is realized every week. As many time as necessary, nets are replaced, frequencies varying with sites. In our exposed and well-flushed area, net changing just before stocking and once during growth (4 to 8 month after stocking) is assumed sufficient. This also provides opportunity to install a mesh size adapted to fish size in order to maximize water exchange. Net changing (16/cycle) involves at least 2 members of staff and takes 1h to 2h depending on the degree of fouling and weather. Once removed, nets are disposed for maintenance by an external company (e.g. *Net services (Shetland) Ltd*). This company provides disinfection, control, repair, antifouling coating and waste disposal for about £850 per net with regards its state and weight. However, the site is equipped with a high pressure cleaner (£1,000), a net drying frame (£5,000) and 560 m^2 (40m*14m) of sloping concrete floor for personal maintenance. This is not the management in place in some square cage systems (R. Hawkins, pers. com.) but is necessary for circular cages. All other equipment such as boats, feeding devices and feed barge need controls and preventive maintenance which are not detailed.

There are several routine operations for the maintenance of a RAS. The high flow rate in the tanks is far above the tank self-cleaning velocity. However, the degree of fouling of tank walls and solid waste deposition at the bottom must be regularly checked. Between each restocking, tanks will be high pressure cleaned (£1,000) to get rid of biofilm growth (1h per tank, 17h per cycle, one staff). During rearing, it may appear necessary to brush walls and/or bottom with individual brushes. Submerged-bead biofilters need to be back flushed as necessary (about once a month) for maximal efficiency. Their conception allows back flushing a quarter of the filter while the remaining keeps working. The foam tank needs to be emptied when necessary, with 30 m^3 stocking capacity and 10% of the flow treated; this is a minor operation realized with a hand effluent pump.

A preventive maintenance plan and the effective control of critical points are determinant in any business, particularly when production security is dependant upon a high degree of technology. All individual devices, e.g. drumfilter, ozonation system, feed barge in both models must have maintenance and control plans. In both systems, 2 % of the Capital Cost is added as Operating Cost for maintenance: £41,209 and £82,058 for respectively cage and RAS models.

3.8. Chemicals

Each system uses several chemicals in order to clean and disinfect devices (Chlorine, iodine, ethanol), treat fish (MS222, Furogen B, Aquagard, Ektoban**)** and protect material (antifouling). These quantities are dependent upon many factors such as site, consent to discharge and management. The total cost of these compounds is assumed similar for each system and low compared to other costs. We consider a total of £10,000 per year, including suitable personal protective equipment. Chemicals used must be carefully managed with appropriate labeling, registration and store which occupies a small surface.

3.9. Human resources

With regards to the operation described, each farm requires 3 workers, 1 manager and 1 multi-talented staff to act as a secretary, accountant and to be in charge of public relation (supplier and sales contacts). For the cage model, one of the staff must have the captain`s license while the RAS model requires at least one engineering specialist. Human resources needed and related costs are identical (Table 3.6).

Table 3.6: Human resources requirement

	Quantity	Salary (£/year)
Manager	1	24.000
Worker	3	16,000
Secretaryship, contacts,…	1	13,000

3.10. Pre-installation, external services and insurance costs

Pre-installation costs include requirement for site detection, design and legal fees, land use and preparation. Therefore, they are mainly dependent on the surface of land required. However, the cage model also required environmental assessment of sea site and sea-grant. Those costs are detailed in appendix C_1.

External services requirement is dependant upon a wide variety of factors such as system conception and personal qualifications; they also vary from year to year. They can not be precisely quantified and the difference between each model is likely to be non-significant. If both models are well managed, some services (professional divers) compensate for others (technical assistance). Therefore, we considered a total of £15,000 for each farm.

Insurance costs are based on *Sunderland Marine Mutual Insurance* experience. From their expertise, they charge aquaculture business in between 3 and 6 % of stock value (sold) depending on many factors such as system, site, management, coverage extension. They consider RAS more risky, therefore the insurance cost is 6 % of stock value (£66,365, maximum biomass on site: 405 t) for the RAS and 3 % of stock value for cage model (£105,768, maximum biomass on site: 1,333 t).

4. Comparative analysis

The aim of this section is to evaluate the overall cost-benefit of the models through financial and environmental analyses in order to highlight their potential, strengths and weaknesses. This requires realistic forecasting and, as much as possible, assumptions made and methods used are addressed. Former parts of this thesis addressed the technical and market choices having made certain assumptions on which basic financial assessment is based. As we compare two production models, these assumptions are likely to vary and some factors such as mortalities and markets prices will be discussed as variables in the sensitivity analysis.

4.1. Basic financial assessment

This initial financial analysis defines basic capital and operating costs for a project operating in full capacity. The aim is to define the fundamental feasibility of the project through profitability and returns to promoters.

4.1.1. Cost analyses and categories

A complete cost listing categorized in its traditional form (Capital and Operating cost listing) is provided in appendix C_1 and C_2.

Capital Cost

Capital Costs (CC) are those required for establishing the system and include, in this analysis, the "pre-establishment costs". A cage farm producing 1,000 t a year of Atlantic salmon requires a Capital Cost slightly over £2,000,000. To achieve the same production capacity with a RAS, the investment is twice as high (Table 4.1) reaching £ 4.1/kg of salmon produce in a year.

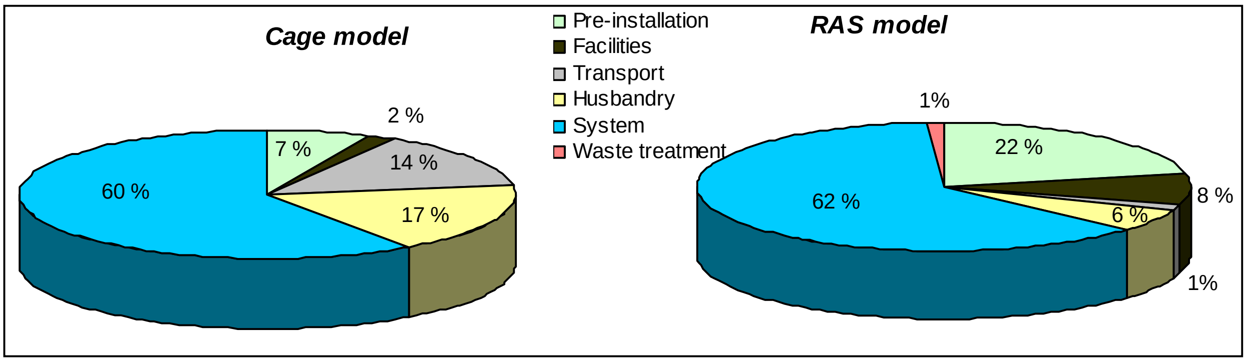
Each Capital Cost is categorized as Variable, Semi-Variable or Fixed (VCC, SVCC & FCC) according to its respective variance with the project's size (respectively proportional, non-proportional and no variance). Each category having the same proportion, no model has a greater potential for economies of scale.

Table 4.1: Capital Cost of cage and RAS models

		Cage model	RAS model
Total CC	(£)	2,060,471	4,102,925
VCC & SVCC	(%)	96.9	97.3
FCC	(%)	3.1	2.7
CC/t production capacity	(£/kg)	2.06	4.10

The pre-installation cost is 6.5 times greater for the RAS at £810,250, due to the requirements of land and its preparation. Facilities cost is very low for the cage model (£35,723) but represents 8 % of the CC for the RAS at £298,723. Despite helicopter and well-boat rental (not included in CC) but due to workboat and voe boat requirements, transport costs represent 14 % of the cage model's CC (£267,000) and are 5.5 time greater than transport cost of the RAS (£48,850). Husbandry cost is 54 % greater in the cage model (£327,452) due to the requirement of materials for treatment and mortalities removal. In the RAS, a simple net is required to remove dead fish against air-lift pump for the cage system. In both models, the cost of the rearing system is dominant with the same proportion: 60 % (£1,119,000) and 62 % (£2,317,109) in respectively cage and RAS models. The feeding barge of the cage model is the main cost of this category (£500,000) (Figure 4.1).

Figure 4.1: Capital Cost categorization



Operating Cost

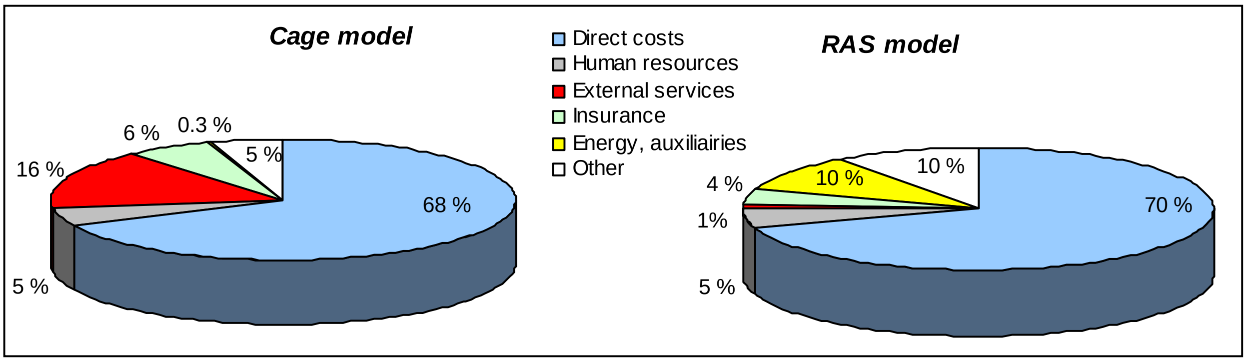
Operating Costs (OC) are those required to run the established system and produce the output. The OC for the cage model is slightly greater (2.6 %, + £46,809) with a total of £1.85/kg of salmon each year against £1.81 /kg for the RAS model (Table 4.2). Fixed OC are minor for both models.

Table 4.2: Operating Cost of cage and RAS models

		Cage model	RAS model
Total OC	(£)	1,853,559	1,806,750
OC/t production capacity	(£/kg)	1.85	1.81

Direct costs (food, fry, oxygen and chemicals) are the main expenses in both cases, slightly higher for the RAS model (£1,141,323 for the cage model; £1,148,933 for the RAS) due to the oxygen requirement but off-set by reduced food consumption. The cost of external services is 18 times greater for the cage model (£266,000 for cages; £15,000 for RAS) due to helicopter and well-boat rental. The cost of energy and O_2 tank rental is far greater for RAS model (£159,151 for RAS; £4,923 for cages) but represent only 10 % of the total OC of this model. The maintenance and business rate, both proportional to the CC, constitute the category "Other" which is therefore higher for RAS model (Figure 4.2).

Figure 4.2: Operating Cost categorization



Depreciation

Depreciation represents the reduction in value of the capital items over time. The output must cover annual depreciation to replace capital parts and run the project over time. The "straight-line method" has been used to give an average amount representing the difference between the initial cost and the residual value divided by the life-span of the component. The annual depreciation is 74 % greater for the RAS model due to the higher capital cost and the reduced average period of depreciation, 8.3 years against 10.2 years for the cage model (Table 4.3). Pre-establishment costs do not depreciate, therefore the depreciation difference between both models is reduced compared to the CC difference.

Table 4.3: Depreciation for cage and RAS models

		Cage model	RAS model
Annual depreciation	(£)	183,372	318,999
Annual depreciation	(£/kg)	0.18	0.32
Average depreciation period	(year)	10.2	8.3

4.1.2. Measures of profit

Measure of profit is dependent upon sales price of salmon. Analysis is based on 3 quality grades, corresponding mainly to freshness and external appearance, with price per kg addressed in table 4.4, assumed from figure 1.3.

Table 4.4: Sales price of whole fresh Atlantic salmon used in the analysis

		Grade 1	Grade 2	Grade 3
Price	(£/kg)	2.30	2.65	2.99
Variation from Grade 1	(%)	0	+ 15 %	+ 30 %

The proportion of sales in each category is dependent upon a wide range of factors. For this primary profit analysis, we considered the distribution among each category for both projects, addressed in table 4.5. The greater proportion of higher quality fish for the RAS is due to higher freshness (continued sales), lower disease rates and corresponding damage. Proportions used here are realistic and conservative; the mean sales price for the RAS is £0.08 greater on average (Table 4.5).

Table 4.5: Repartition of sales by quality grades for both models and related income

	Grade 1 (%)	Grade 2 (%)	Grade 3 (%)	Mean sales price (£/kg)	Income (£)
Cage model	20	60	20	2.65	2,644,202
RAS model	10	55	35	2.73	2,731,674

Based on incomes and cost analyses addressed, a range of financial indicators can be developed (Table 4.6). Such indicators are useful to compare the profitability of models producing their full capacity. The unit production cost is 8 p. greater for the RAS (+ 4.7 %); both models produce salmon with a break-even price under the market price and so are potentially viable. Thanks to the greater gross profit for the RAS (+ 17.6 %), the net profit of both models is similar and slightly higher for the RAS (+ 0.5 %), therefore profitability ratios (Net profit/annual sale income) are also similar. The payback period, (period to recover the money invested), is almost twice as short for the cage model as for the RAS model (respectively 2.6 and 4.4 years) which reflects CC differences due to similar net profit. The Return On Investment (ROI) shows a similar trend with a smaller difference since this ratio includes OC (Net profit/ (CC+OC)*100). The ROI is 15.5% per year of the money invested against 10.3 % for cage and RAS models respectively; both rates are higher than bank interests for deposit. Energy consumption per t produced is addressed in table 4.6.

Table 4.6: Indicators of profitability

		Cage model	RAS model
Unit production cost	(£/kg)	2.04	2.12
Gross profit	(£)	789,126	928,151
Net profit	(£)	605,754	609,153
Profitability ratio		0.23	0.22
Payback	(year)	2.6	4.4
Simple Rate of Return	(%)	29.4	14.8
Return On Investment	(%)	15.5	10.3
Energy consumption	(kW/t)	87.6	4,030

4.2. Advanced financial assessment

This part aims to define not just the viability of the project, but also the actual returns to the owners. This can be achieved by identifying the rate of project build-up and incorporating time value of money, means by which the project is financed and the effects of taxation.

Analysis is based on a 2-year project build-up in both cases, but with different rates. The cage farm has half its capacity installed and fully stocked the first year against one third for the recirculation project (one grow-out system out of three).

4.2.1. Cash flow

The Net Present Value (NPV) is the sum of the annual benefits in present value, which means that they are modified by a discount rate (8 %). The Internal Rate of Return (IRR) is the discount rate at which the sum of the discounted cash flow is equal to 0. The period used for these indicators is usually 10 years (number of years in operation) after the period of start-up, which makes 11 years in this study. After this period, both model's NPV are positive, and so the IRR is more than the discount rate used; the investment is economically feasible (Table 4.7). However, with a IRR under 25 %, the RAS model appears far less profitable. A period of 10 years is too short to give a significant return in present value due to the high CC.

Table 4.7: Net Present Value and Internal Rate of Return (10 years)

		Cage model	**RAS model**
Net Present Value	(£)	2,252,600	106,800
Internal Rate of Return	(%)	33.1	8.5

4.2.2. Financing

Capital Cost is financed by equity (personal resource of investors) and by long-term bank loans. The working capital (operating cost before revenue from sales) is financed by a short-term bank loan in order to maintain a positive cash flow over the year. Revenue from 1st year sales is used to cover the OC of the 2nd year, but only partly, due to projects` build-up.

The equity assumed is about 13 % of the total CC, a total of £300,000 for the cage model and £500,000 for the RAS model. The long-term loan required is twice as important for the RAS model with a total of £3,600,000. This loan at 8 % is repaid over 10 years, giving a mean annual repayment of £360,000 for a total charge of £1,584,000 over the period. The short-term loans requirement is slightly higher for the RAS model (+£140,000). The higher investment needed for the RAS required higher loans inducing an extra financial cost of £799,680 in total (Table 4.8).

Table 4.8: Financing plan and related cost (£)

		Cage model		RAS model	
		Year 1	**Year 2**	**Year 1**	**Year 2**
Capital Cost		1,557,661	502,810	2,281,092	1,821,833
Working capital		927,538	1,855,076	595,163	1,269,323
Equity		200,000	100,000	400,000	100,000
Long-term loan	Period: 10 y. Interest: 8 %	1,360,000	400,000	1,900,000	1,700,000
	Total Charge	798,720		1,584,000	
Short-term loan	Period: 1 y. Interest: 12 %	930,000	800,000	600,000	1,270,000
	Total Charge	210,000		224,400	

4.3. Risk analysis and environmental economics

Risk analysis is a particularly important process for aquaculture, which involves live stock and technology. The aim is to define the potential deviation from the expected outcome in order to obtain a more realistic figure of the financial interest of the investment.

This risk analysis takes into account the traditional mix between risk-taking and risk-averse investment, with mitigation measures included in the farm set-up and optimal management assumed. The analysis is based on projects once installed, and therefore does not take into account planning, design and building risks. This whole study is far from taking into all installation parameters; however, projects are based on Atlantic salmon rearing which is probably the best known biological model. The 1,000 t RAS may appear as a pioneer project. However, with a maximum biomass of 200 t per system, the size of the system is not so unusual and the need for a complete design and a pilot farm is recognized. Farm sitting is a major determinant for precise risk analysis so mean figures are used.

Finally, it is important to consider risk related costs with insurance. Insurance is an expense which equalizes risk costs over the years. However, some risks are not covered and insurer perception of a system evolves with environmental conditions and experience in the production system used. Therefore, cost of risks identified here will be added to the initial financial analysis which includes insurance cost.

4.3.1. Risks identification

Both projects being compared share the same general location; the United Kingdom. We do not therefore consider political, financial or market risks which are generic and would similarly affect both projects. Three categories of risks are identified as having specific impacts on each project; they are listed in table 4.9, 4.10 and 4.11 along with their effects.

Table 4.9: Ecological/Environmental risks

Cage model		RAS model	
Origin	**Effect**	**Origin**	**Effect**
Physical risks			
Storm, rough sea Water velocity	Fish damage Poor growth Stock transfer delay Structure damage Disease sensitivity	Air T° Hail Snow Wind	Building, system damage
Chemical risks: Water Quality			
Ext. variation T°, O_2, pH, turb. **Ext. pollution** Industry, agriculture, boat ballast **Int. pollution** Sediment deterioration, chemical	Mortalities, poor growth, disease sensitivity	**Ext. pollution** Industry, agriculture, boat ballast	Mortalities, poor growth, disease sensitivity
Biological risks			
Pathogen Parasite Algal/jellyfish bloom Predator Scavengers	Mortalities - Poor growth, Downgrading Structure damage Disease sensitivity	Pathogen, parasite, algal/jellyfish bloom	Mortalities - Poor growth, Downgrading Structure damage Disease sensitivity

Table 4.10: Technical risks

Cage model		RAS model	
Origin	**Effect**	**Origin**	**Effect**
Pen/Net/Mooring Feeders Sonar system Tarpaulins Predator device Feed barge	Fish loss Inadequate feeding Inadequate feeding Treatment inefficiency Structure damage Stress No feeding, data loss	Pumps Feeders Sonar system Oxygen system Biofilter Drumfilter Ozonation	Water shortage Inadequate feeding Inadequate feeding Fish toxicity Fish mortality

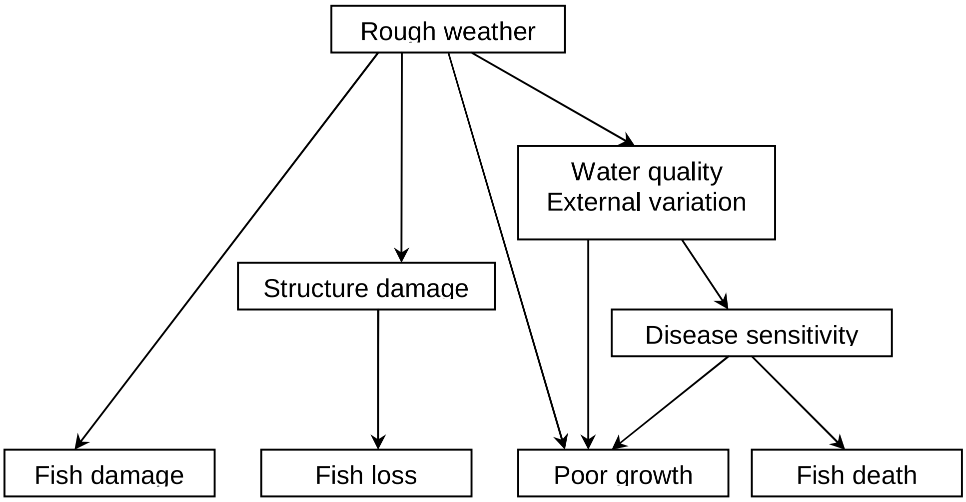
Table 4.11: Social/human risks

Cage model		RAS model	
Origin	**Effect**	**Origin**	**Effect**
Vandalism Supplier shortage Human errors	Structure damage Mortalities - Poor growth – Structure deficiency	Vandalism* Supplier shortage Human errors	Structure damage Mortalities - Poor growth – Structure deficiency

4.3.2. Risks classification through probability and magnitude

Identified risks are interrelated. They may be the direct source of a negative effect, but they may also be induced by another source and so act indirectly. Figure 4.3 and related table 4.12 show an example applied to the cage model, rough weather, given to illustrate the method used to obtain the risks classification.

Figure 4.3: Risks representation from rough weather, cage model



Rough weather is defined as an unusually strong wind which induces high waves, “unusual” meaning it occurs in average 4 days per year, 1.1 % of the year, 1.5 % of the cycle. High water velocity directly induces:

(1) Fish damage (net abrasion): 2 % of stock downgraded, 35p/kg lost

(2) Poor ingestion (50 % FR), activity increase and stress (FCR + 20 %)

Cages are built to support this rough weather since the standard is to design for the worst forecasted weather over the next 30 years. However, mismanagement and wear can lead to structure damage, with several potential cases:

(3) Mooring damage from one cage: stock recovered, only material cost

(4) Slight net damage: 2 % Loss of stock from 1 cage

(5) Major net damage: 90 % Loss of stock from 1 cage, material cost

Rough weather can also induce water quality variation such as salinity from freshwater and turbidity from land run-off. These water quality variations induce a stress:

(6) Poor ingestion: 50% of feeding rate

(7) Disease sensitivity: Outbreak probability from 10 % to 20 %, material cost: £24,000

This potential disease (7) has a direct cost for treatment and management but also induces:

(7a) Poor ingestion: 50% of feeding rate during development (1 week)

(7b) Growth loss during treatment, no ingestion (4 days)

(7c) Mortality on farm (1% from disease and treatment)

The individual probability and cost of these events are summarized in table 4.12 to finally obtain the global probability of negative consequences from rough weather (0.675 %) and the related costs (£54,728).

Table 4.12: Risk analysis from rough weather, cage model, based on half-load (666 t) and price sales of £2.65/kg

	Probability (%)		Biomass involved		Material loss (£)
	When rough weather	**With rough weather prob.**	**kg**	**£**	
(1)	90	1.35	13,500	2,700	-
(2)	90	1.35	6,120	13,464	-
(3)	5	0.075	-	-	11,000
(4)	30	0.45	2,500	5,500	-
(5)	5	0.075	112,500	247,500	5,850
(6)	75	1.125	5,290	11,638	-
(7)	20	0.3	32,560	71,632	24,000
(7a)	*20*	*0.3*	*14,760*	*32,472*	
(7b)	*20*	*0.3*	*7,800*	*17,160*	
(7c)	*20*	*0.3*	*10,000*	*22,000*	
Total		**0.675**	31,257	**54,728**	**2,693**

The same method has been developed for each risk addressed in table 4.9, 4.10 and 4.11 to obtain results summarized in table 4.13, figure 4.4, 4.5, 4.6 and 4.7. External variations of water quality is not analyzed since its effects are included in growth cycle (FCR = 1.3 and FR varies with water temperature).

Over the year, the mean probability for a loss to happen is 40.9 % for the cage model against 8.4 % for the RAS model (addition of individual risks). This is mainly due to non manageable environmental risk for cages and high probability of treatment inducing biomass loss while technical risk appears reduced for the RAS, assuming good design and maintenance. Weighed biomass and financial losses are similar (Table 4.13). Despite a mean biomass reduced on site (life cycle length and regular output) and the independence of the 3 grow-out systems for the RAS, massive loss can be induced by various potential technical problems. The annual cost of risks is more than 4 times greater for the cage model with £62,772, £0.063/kg of salmon produced.

Table 4.13: Average risk probability and financial loss

		Cage model	RAS model
Mean probability	(%)	40.9	8.4
Weighted biomass loss	(kg)	54,271	47,553
Weighted cost	(£)	137,255	115,877
Mean annual loss	(£/year)	62,772	14,938
	(£/kg)	0.063	0.015
	(% stock value)	2.4	0.5

Disease outbreak is the main risk for both models and has a probability over 50 % to be the losses` origin when losses occur (Figure 4.4 and 4.5). Related costs from this risk are more precisely addressed in table 4.14. In the cage system, loss from disease outbreak has the highest probability (24.4 %) and the highest related cost (£190,500). The second risk, predator related loss (7.6 %), has lower financial consequences (£42,500). Other significant risks for this model in term of probability and loss are environmental (algal bloom) and social (vandalism) (Figure 4.6). The risk of a major technical problem on a cage could induce a massive loss of £169,500 but has a low probability. The risk of internal and external pollution is reduced due to water velocity on site; human error even probable does not induce a high loss.

For the RAS model, disease outbreak has a reduced probability and cost (5.4 %; £129,700). The second risk is human error (2.1 %) due to system complexity, uniqueness and full dependence on human management. The mean financial loss is reduced since many errors do not induce critical loss. Significant risks in term of financial loss, such as oxygen system or biofilter malfunction have low probability (Figure 4.7) when taking into accounts regular maintenance, safety devices and the fact that many technical operations are done by several components in one system, e.g. filtration by 2 drumfilters.

Figure 4.4: Risk ranking for cage system (logarithmic scale)

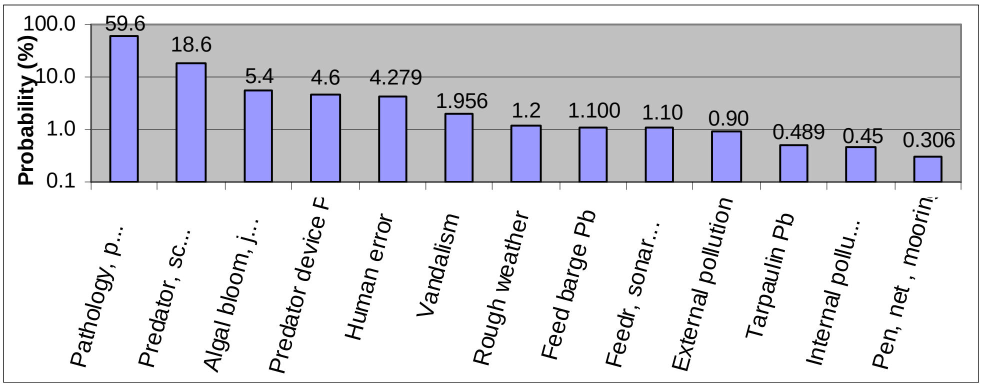


Figure 4.5: Risk ranking for RAS (logarithmic scale)

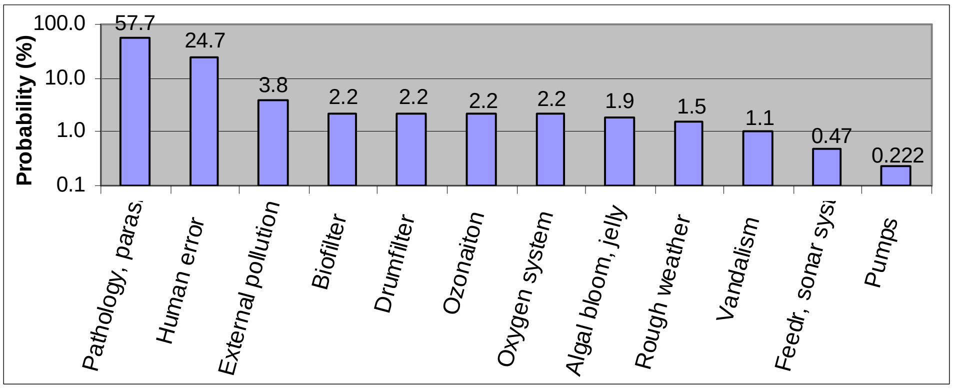


Figure 4.6: Mean risk probability and weighted cost per risk source in cage system (Sales price: £2.65/kg)

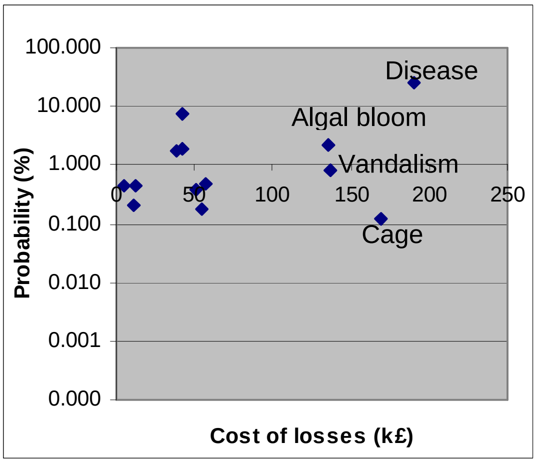


Figure 4.7: Mean risk probability and weighted cost per risk source in RAS (Sales price: £2.89/kg)

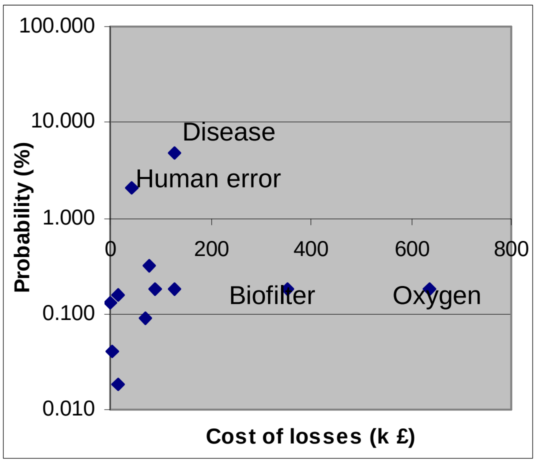


Table 4.14: Cost of disease outbreaks

		Cage model	RAS model
Probability	(%)	25	5
Mean total cost	(£)	169,000	108,000
Mean total cost	(£/year)	42,250	5,400
Mean total cost	(p/kg)	4.2	0,54

4.3.3. Environmental economics

This section aims to identify and quantify environmental effects of projects through cost estimation. Resources availability for other users, sustainability of production processes and ecosystem changes have a cost. Table 4.15 addresses a summary of environmental consequences specific of cage aquaculture. Chemical and pathogen release is not addressed, as it may also apply to RAS. No environmental consequences specific to RAS have been identified even if some exist such as the potential for leakage of seawater on land, greater energy consumption and carbon emission. Those costs appear low and compensate for the non considered food-web modifications from cages system.

Table 4.15: Environmental costs analysis

Source	Effect	Proba.	Magni.	Cost	Costing factor
Organic waste	Impact on sea-bed	Low	Low	0	Regeneration Dispersion Reduced water quality
	Food web modification	Low	Low	0	
	Eutrophication	Low	Low	£0.40/kg* £0.18/kg	
	Habitat fragmentation	Low	Low	0	
Feral	Competition and predation	High	Medium	-	Wild replenish
	Disease spread	Medium	Medium	£0.062/kg	Wild depletion Fisheries degradation
	Genetic degradation	Medium	High		
Predators	Disease spread	Medium	Medium		
	Community displacement	High	Low	-	Food web
	Effect on non target-species (protection devices)	Medium	Low	-	Food web

**Folke et al (1992)*
- Non priced environmental costs

Organic waste has low consequences due to the exposed sitting of the cage site but recuperation and remediation cost would be high. Eight curtains bags equipped to recover solid waste and pumps to renew 50 % of the water per hour (35,220 m^3/h) would cost at least £450,000, £0.11/kg of salmon with 4 years depreciation. The related operating costs are about £0.07/kg without consideration of probable oxygen requirement. Waste can then be treated as land-based waste. The eutrophication cost for the cage farm is £0.18/kg salmon from this rough analysis.

Disease spread and genetic degradation contribute to wild stock depletion and are likely to happen. The consequence in terms of wild salmon quantity is off-set by escapee themselves but wild salmon quality suffers. Sustainability of the species cannot be priced for future generations of professional and leisure fishermen, for aquaculturists (gene pool) and for the ecosystem. In order to remedy this problem, we considered that for each farmed salmon reproducing in the wild, 4 wild salmons from stock enhancement should reproduce. Therefore, if 3 % of smolt stocked escape (average) and 10% reproduce in wild (978 for the cage model), it would be necessary to release 39,120 smolts, 10 % of which will survive to reproduce. This could be done by wild fry ranching and reproduction. With commercial smolt hatcheries producing smolt for £0.08, this specific management is likely to produce smolt of at least p1.6 which would cost £62,592 for the farm, £0.062/kg. Many environmental effects inducing food web changes are not priced since they are poorly known.

4.4. Sensitivity analysis: consequences on financial return

A sensitivity analysis classically aims to define the effects on profit resulting from changes in the main input capital or operating components. The effect of risks and environmental costs is also addressed here.

What if we do not consider the "pre-establishment" Capital Cost?

The "pre-establishment" costs constitute 7 % and 22 % of the OC for respectively cage and RAS models. They are not always included in the financial analyses while they may be reduced if land is owned or if only few preparations are required (e.g. no strip vegetation and top soil removal). However, these costs do not depreciate and so the net profit and related ratios (e.g. pay-back period, unit production cost) addressed before are not modified.

With exclusion of these costs, the RAS model has a total CC 66.9 % higher instead of 99.1 % (£3,211,650 instead of £4,102,925). As a result, the difference in NPV and SRR between both models is reduced. The SRR of the RAS is now equal to 15.4 %, but still under 25 % which is the minimal target for aquaculture projects. The extra financial cost from bank loans for RAS compared to the cage model is reduced to £468,560 instead of £799,680 when "pre-establishment" costs are included (Table 4.16).

Table 4.16: CC, NPV, SRR and bank loans when "pre-establishment" cost are excluded

		Cage model	RAS model
CC	(£)	1,924,093	3,211,650
Comparison	(%)		+ 66.9 %
NPV	(£)	2,389,000	981,800
SRR	(%)	36.7	15.4
LT loan	(£)	1,620,000	2,710,000
ST loan	(£)	1,750,000	1,870,000
Total charge	(£)	948,240	1,416,800

What if we include the cost of risks?

Risks have a cost mainly by reducing output. Therefore, the annual cost of risks (Table 4.13) is subtracted from the sales value for both models; Operating Costs are not modified. Therefore, unit production costs are not modified but they slightly change in reality (e.g. treatment). In this case, the RAS has a Net profit about £50,000 greater than the cage model (+ £0.005/kg, £0.059/kg). The latter keeps a better indicator with a SRR remaining above 25 %, but decreasing by 10.3 %, and a payback period still under 3 years. The cash-flow analysis shows the IRR of the cage model is reduced by 5 %, from 33.1 % to 28.1 % (Table 4.17). The NPV of the RAS is almost nil after 10 years of full-scale production with a discount rate of 8 % (Table 4.17) against £106,800 when excluding risk and including pre-establishment cost. The business profitability analysis is more realistic when risk costs are included.

Table 4.17: Indicators of profitability, NPV and IRR, including risks cost

		Cage model	RAS model
Unit production cost	(£/kg)	2.04	2.12
Net profit	(£)	542,982	594,215
Profitability ratio		0.21	0.22
Payback	(year)	2.8	4.5
Simple Rate of Return	(%)	26.4	14.5
Return On Investment	(%)	13.9	10.1
Net Present Value	(£)	1,799,900	1,600
Internal Rate of Return	(%)	28.1	8.01

What if we include environmental costs?

As addressed in table 4.15, the internalization of environmental costs would increase production cost by total of £0.26/kg of salmon produce: £0.20/kg for eutrophication remediation and £0.06/kg to manage the impact on wild stock. This corresponds to an increase in OC of £260,000 to reach £2.3/kg of salmon for the cage against £2.12/kg for the RAS model (Table 4.18). Profitability ratios addressed in table 4.18 include risk and environmental costs. If the "polluter-pays" principle is applied, the cage model appears less profitable than the RAS model with a Net profit and profitability ratio twice as small. The capital invested is paid-back in 4.5 years for both projects, but the CC remains twice as high for the RAS. The SRR is only slightly inferior for the cage model, with the smaller CC compensating for the reduced Net profit. The ROI is only 6.8 % for the cages and 10.1 % for the RAS, net profits being weak in front of OC and CC for both models. The cash-flow analysis gives a negative NPV for cages at 10 years of full production; therefore the IRR is under the discount rate.

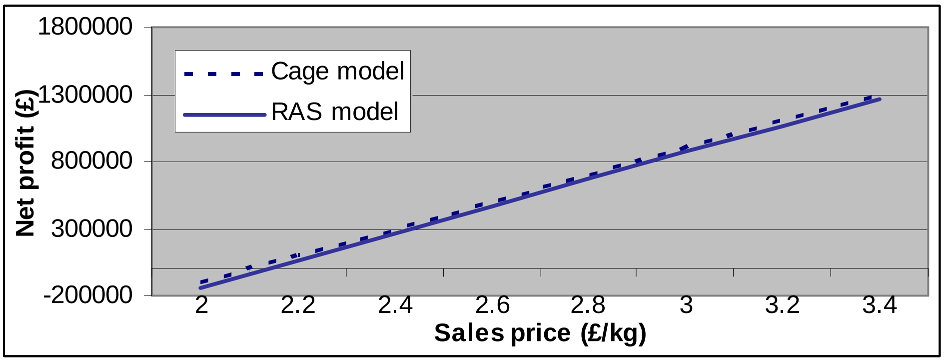
Table 4.18: Indicators of profitability, NPV and IRR, including risk and environmental costs

		Cage model	RAS model
Unit production cost	(£/kg)	2.30	2.12
Net profit	(£)	282,982	594,215
Profitability ratio		0.11	0.22
Payback	(year)	4.4	4.5
Simple Rate of Return	(%)	13.7	14.5
Return On Investment	(%)	6.8	10.1
Net Present Value	(£)	-74,600	1600
Internal Rate of Return	(%)	7.11	8.01

What if the sales price of whole Atlantic salmon varies?

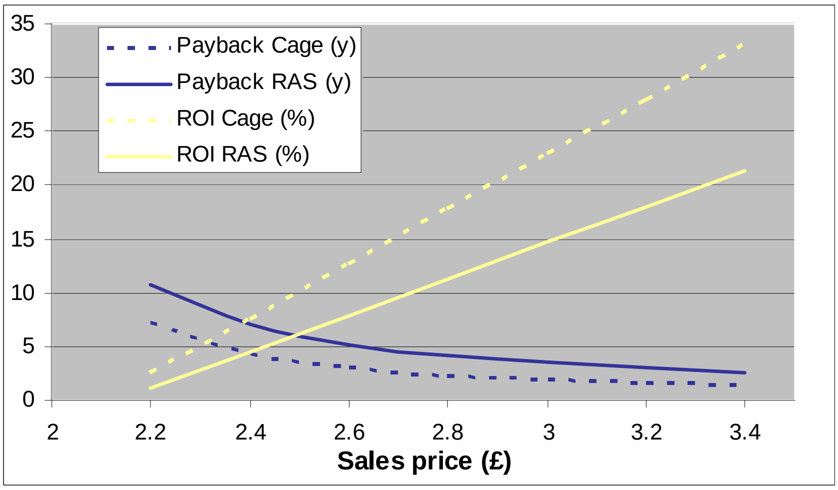
This sensitivity analysis includes risk cost but not environmental cost. For a sale price of £2.0/kg, the Net profit of both projects is negative due to a higher break-even price. The difference of Net profit between the two models (£32,500) remains stable when price varies and is minimal with regards to the effect of sale price (Figure 4.8). For any given model, such a Net profit increase is achieved by a sales price increased by less than £0.17/kg.

Figure 4.8: Evolution of the Net profit with regards to the sale price of Atlantic salmon



An increase in the mean sale price reduces the difference between the payback periods but increases the difference of the Return On Investment between models (Figure 4.9). The difference in the NPV also increases along with sales price: +£ 2,338,700 for the cage model at a sale price of £2.4/kg. In periods of poor market price, the ROI and the NPV of the RAS model are closer to those of the cage model. A ROI of 15 % is reached by cages with a sales price of about £2.7/kg against £3.0/kg for the RAS.

Figure 4.9: Evolution of the payback period and the Return On Investment with regards to the sale price of Atlantic salmon



What if the difference in quality of salmons from cage and RAS varies?

This sensitivity analysis includes risks cost but not environmental cost.

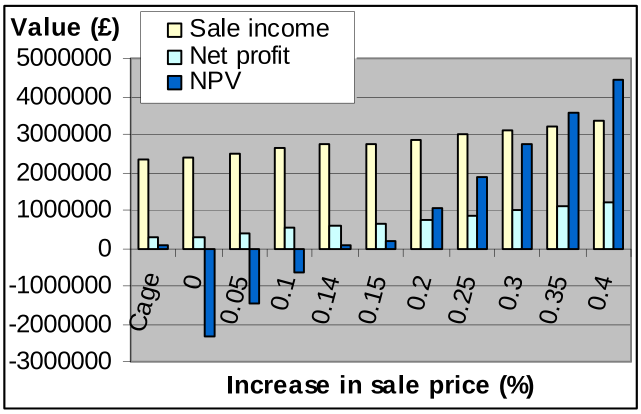
The initial analysis was based on a 3.2% premium on price for the RAS products (Table 4.5) which is probably a conservative assumption. The sales price of salmon from RAS could be higher when taking into consideration freshness, appearance and consumer perception. From a sale price of £2.4/kg for the cage model, we studied the effect of a premium price from 0 to 40 % for the RAS products (Table 4.19).

The Net Present Value of the RAS cash-flow is equal to the one of the cage model when the RAS get a premium of 14.1 % on its sales price (£2.74 against £2.4) (Figure 4.10). This higher level of mean sales price can be obtained if sales of models are split in the 3 quality grades as shown in table 4.20. The ROI is equal for a premium under 10 %, as is the payback period for a premium of 15 %. If the RAS model reaches a 20 % higher mean sale price, it can obtain a NPV above 10 times greater than the cage model, a ROI of 12.6 % and a payback reduced to 3.9 years (Figure 4.11).

Table 4.19: Potential premium on sale price used

	Variation from cage model sale price (%)	Sale price (£/kg)	Premium (£)
Cage	-	2.40	
RAS	0.00	2.40	0.00
	0.05	2.52	0.12
	0.10	2.64	0.24
	0.14	2.74	0.34
	0.15	2.76	0.36
	0.20	2.88	0.48
	0.25	3.00	0.60
	0.30	3.12	0.72
	0.35	3.24	0.84
	0.40	3.36	0.96

Figure 4.10 and 4.11: Income, Net profit, NPV, payback period and ROI levels with regards to price premium obtained by RAS. Cage values are provided for comparison, based on a £2.4/kg sale price.



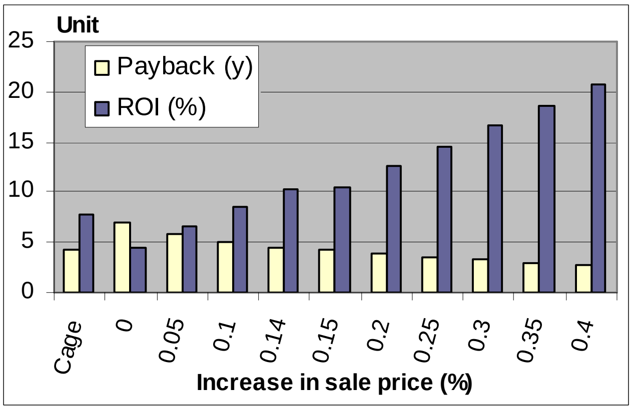


Table 4.20: Proportion of sales grade (given with prices) necessary for the RAS to get a mean premium of 14.1 % and obtain NPV and payback period similar to the cage model

	Variation from G1 (%)	Price (£)	Cage model (sales %)	RAS model (sales %)
Grade 1	0	2.3	31	5
Grade 2	+ 15	2.65	64	10
Grade 3	+ 30	2.99	5	85
Mean sale price (£/kg)			2.56	2.92

What if the FCR varies?

The financial results from varying biological performance are compared, based on the initial sales repartition (Table 4.5) and including risks cost. We assumed the biological performances are anticipated by farmers from experience, therefore, FCR variation results in both smolt stocked and food consumed variation to reach the targeted production of 1,000 t per year. From a FCR of 1.3 for the cage model and 1.2 for the RAS model (- 7.7 %) on which previous analyses are based, the consequence of FCR improvement in the RAS model is addressed in table 4.21. Roughly, the RAS net profit improves by £12,000, for a FCR improvement of 1 % (0.01 unit). Financial results, particularly NPV at 10 years, are improved as shown in table 4.21. When FCR improves by 5 %, ROI improves by 1 %. However, a FCR of 1.08 is not sufficient for the RAS to obtain financial results as good as those of the cage model having a FCR of 1.3 (+ 17 %).

Table 4.21: Variation of Operating Cost and ratios of profitability from FCR improvement of the RAS model, compared with Cage model having a FCR of 1.3

	FCR (%)	FCR	Variation of OC (£)	Net profit (£)	ROI (%)	Payback (y.)	NPV at 10 years (£)
CAGE	**-**	**1.3**	**-**	**542,982**	**13.9**	**2.8**	**1,799,900**
RAS	1	1.2	0	594,215	10.1	4.5	1,600
	0.99	1.19	-12,890	607,105	10.3	4.4	92,300
	0.98	1.18	-26,570	620,785	10.5	4.4	188,500
	0.97	1.17	-39,140	633,355	10.7	4.3	277,300
	0.96	1.15	-52,420	646,635	10.9	4.2	370,800
	0.95	1.14	-63,880	658,095	11.1	4.2	451,300
	0.94	1.13	-76,920	671,135	11.4	4.1	543,200
	0.93	1.12	-89,010	683,225	11.6	4.1	628,300
	0.92	1.11	-100,150	694,365	11.8	4.0	706,700
	0.91	1.09	-110,340	704,555	11.9	4.0	778,400
	0.90	1.08	-121,160	715,375	12.1	3.9	854,700

Table 4.22 addressed the consequence of FCR variation of cage model compared to RAS. Roughly, the cage model net profit is improved by £19,000 for a FCR improvement of 1 % (0.01 unit). The greater mean biomass on site for this system induces a greater financial sensitivity to variation of biological performance. When FCR improves by 5 %, ROI improves by 2.9 %. If cages reach a FCR of 1.24 against 1.20 for the RAS model, the payback period of cages is reduced to 2.5 years against 4.5 years for the RAS system (Table 4.21). Both the RAS and the cage models have the same ROI if they reach a FCR of 1.08 and 1.34 (+ 19.4 %) respectively. Equal NPV requires a FCR about 22 % higher for RAS (1.07 against 1.37), which would also provides a RAS payback almost as quick as that of the cage (Table 4.21 and 4.22).

Table 4.22: Variation of Operating Cost and ratios of profitability from FCR variation of the cage model, compared with RAS model having a FCR of 1.2

	Sensitivity Coefficient	FCR	Variation of OC (£)	Net profit (£)	ROI (%)	Payback (y.)	NPV at 10 years (£)
RAS	**-**	**1.2**	**-**	**594,215**	**10.1**	**4.5**	**1,600**
CAGE	0.95	1.24	-96990	639,972	16.8	2.5	2,499,300
	0.96	1.25	-77717	620,699	16.2	2.5	2,360,200
	0.97	1.26	-56790	599,772	15.5	2.6	2,209,500
	0.98	1.28	-40390	583,372	15.1	2.7	2,091,100
	0.99	1.29	-18300	561,282	14.4	2.8	1,932,000
	1	**1.30**	0	**542,982**	**13.9**	**2.8**	**1,799,900**
	1.01	1.31	20880	522,102	13.2	2.9	1,649,500
	1.02	1.33	40190	502,792	12.7	3.0	1,510,200
	1.03	1.34	59800	483,182	12.2	3.1	1,368,800
	1.04	1.35	81130	461,852	11.6	3.2	1,215,000
	1.05	1.37	99440	443,542	11.0	3.3	1,083,000

What if mortalities vary?

In this case, we assumed that the level of mortalities predicted is the one corresponding to the sensitivity coefficient of 1 in the table 4.23. Therefore, mortalities variation results in sales income modification with impact on financial results.

As shown in table 4.23, the RAS is allowed a maximum mortality of 5 % in order to get a positive NPV at 10 years. With mortality rate inferior by more than 10 %, the profitability of the RAS remains under the profitability of the cage system. The window of potential annual mortality has a minor impact on the comparative profitability of the two systems.

Table 4.23: Variation of sales income and ratios of profitability from variation of mortalities

	Sensitivity Coefficient	Mortality (%)	Production (t)	Income variation (£)	Net profit (£)	ROI (%)	Payback (y.)	NPV, 10 years (£)
RAS	2	10.3	947	-144,756	482,192	8.2	5.1	-787,000
	1	5.3	1,000	0	594,215	10.1	4.5	1,600
	0.5	2.7	1,028	76,475	652,526	11	4.2	411,900
CAGE	1.5	15.3	946	-142,830	418,201	10.8	3.4	1,110,300
	1	10.5	1,000	0	513,887	13.1	3.0	1,799,900
	0.5	5.4	1,057	150,765	615,123	15.5	2.6	2,530,000

What if energy cost varies?

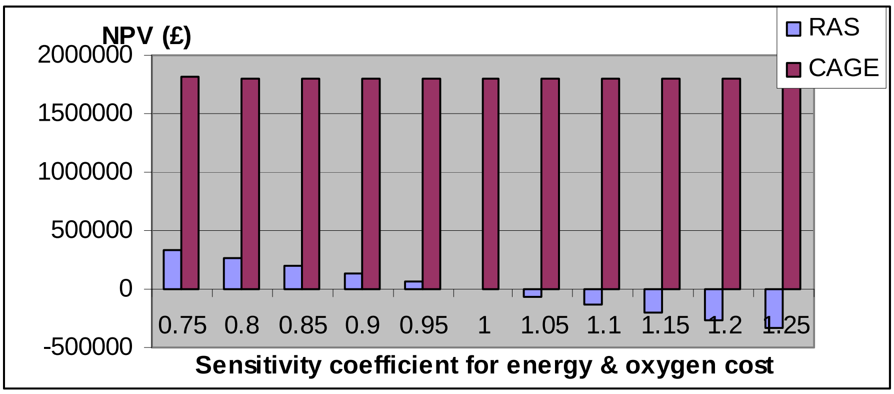
Energy and production auxiliaries (oxygen) constitute 10 % of the Operating Cost for the RAS model against 0.3 % for the cage model while other OC categories are similar (Figure 4.1 and 4.2). Therefore, the cost of energy variation with time or space has the potential to influence the comparative profitability of the systems.

If the cost of energy decreases by 25 %, the Net profit of the cage model is increased by £1,200 against £47,000 for the RAS. As a consequence, the NPV at 10 years of the RAS increases by £330,000 (Table 4.24). However, with regards to the difference in the initial profitability and the dominance of other OC (direct cost), the variations of energy cost does not modify significantly the comparative profitability of the models (Figure 4.12).

Table 4.24: Variation of ratios of profitability from variation of energy and oxygen prices

	Sensitivity Coefficient	Net profit (£)	ROI (%)	Pay back (y.)	NPV (£)
CAGE	0.75	544,213	13.9	2.8	1,808,800
	1.00	542,982	13.9	2.8	1,799,900
	1.25	541,757	13.8	2.8	1,791,200
RAS	0.75	641,247	10.9	4.3	332,700
	1.00	594,215	10.1	4.5	1,600
	1.25	547,182	9.3	4.7	-329,500

Figure 4.12: Variation of NPV from variation of energy and oxygen costs



5. Discussion

Models legitimacy

According to table 5.1, production cost of both models appears high. The cage model has a production cost only £0.06 lower than the one found by Bjørndal (1990) for the Norwegian industry (£2.10/kg) and £0.54 higher to the one assumed by Prickett R. (£1.50/kg) from comparison with Cod land-based rearing. However, our model is design for medium exposed conditions, as required for further development of the industry, involving a higher capital cost than traditionally performed by the industry. *Inter Aqua Adv. Aps* claims Freshwater RAS produce Rainbow trout for £1.58/kg while our seawater RAS gives a breakeven price of £2.12/kg.

Table 5.1: Production cost for different system and species

System	Species	Year	Scale (t/year)	Prod. cost (£/kg)	Reference
(1) Cage	A. salmon	2004	1,000	**2.04**	Present thesis
(2) RAS	A. salmon	2004	1,000	**2.12**	Present thesis
(3) Cage	A. salmon	2003	Large	**1.50**	Prickett R.
(4) Land-based	Cod	2003	Large	**2.06**	Prickett R.
(5) Cage	Cod/Haddock	2003	1,000	1.56	Slaski, RJ
(6) Cage	Halibut	2003	500	2.42	Slaski, RJ
(7) Land-based	Halibut	2003	200	3.26	Slaski, RJ
RAS	Rainbow trout	2003	600	1.27	Inter Aqua Adv. Aps
RAS	Barramundi	2003	600	1.58	Inter Aqua Adv. Aps
Cage	A. salmon	1990	250	2.10	Bjørndal T.

Getting more into details of production costs, origins of these variations are specified. With regards to table 5.2 and figure 5.1, the depreciation appears high in our models. Even if the design is rough, the costing is high enough and may be exaggerated due to a 10 % contingency added to cover extra costs. Moreover, prices here are mainly based on the latest material available while, in reality, a farm would probably find more cost effective options and prices discounts. The price of juveniles is similar to the one assumed by Prickett (2003). The mortality rates used (5% RAS and 10% cage) are discussed earlier as realistic. The price of food is higher in models developed. Earlier, in both models, supplied food is used which however may not be the best option.

Moreover, the scale of our production and specific agreement may allow for extra discount. The FCR used (1.2 for RAS and 1.3 for cage) may be excessive in regards of actual performance among the industry but the high water velocity (cage) may not allow it to reach the present performance of a traditional system. However, the difference in RAS and cage FCR is realistic and probably conservative. On the other side, labour cost appears low (£0.09/kg against £0.20/kg; Prickett, 2003). However, this manager assumed the same staff productivity (200 t/man a year) and about the same time to market (15 months) for a cage system, while the salary used in this analysis are appropriate for average experienced staff (Table 3.6). Main difference is observed in the category “Other” (£0.53/kg against £0.18/kg; Prickett, 2003). For the cage system, the well-boat rental for 44 days is the main component of this category. A distance of 50 km from the processing plant is considered for a new site development due to the occupation of ideal sites. This distance is realistic but discount and specific management by multi-site companies may allow reducing this cost. The category “Other” of the RAS includes mainly energy and oxygen and is more than 3 times greater than the value given by Prickett for Cod land-based rearing system (pump ashore) (£0.57/kg against £0.18/kg). The energy and oxygen budget has been relatively precisely studied with safety and contingency margins. Energy costs are usually said to be excessively high in RAS to be competitive compared to cage system. It is effectively a high part of OC in traditional RAS (30 % OC for Lochailort Smolt Unit, J. Orbell, pers. com.) but account for only 10 % of OC in the RAS developed in this study, thanks to smaller recirculating rate, building disposition, air management and cooling by heat exchange. The installed power (358 kW) is in accordance with a smolt RAS similar to the model addressed in this study, in final phase of construction and showing good preliminary results (Table 5.2).

Table 5.2: Repartition of production cost of different systems and species

See Table 5.1		(1)	(2)	(3)	(4)	(5)	(6)	(7)
Juveniles	**(%)**	10	10	15	23	28	42	30
Feeds	**(%)**	46	41	52	47	39	30	22
Salaries	**(%)**	4	4	13	14	10	7	13
Depreciation	**(%)**	9	15	7	6	10	7	7
Insurance	**(%)**	5	3	13	10	2	2	2
Other	**(%)**	26	27			11	12	26
Production cost	**(£/kg)**	2.04	2.12	1.50	2.06	1.56	2.42	3.26

Figure 5.1: Production cost structure of different system and species

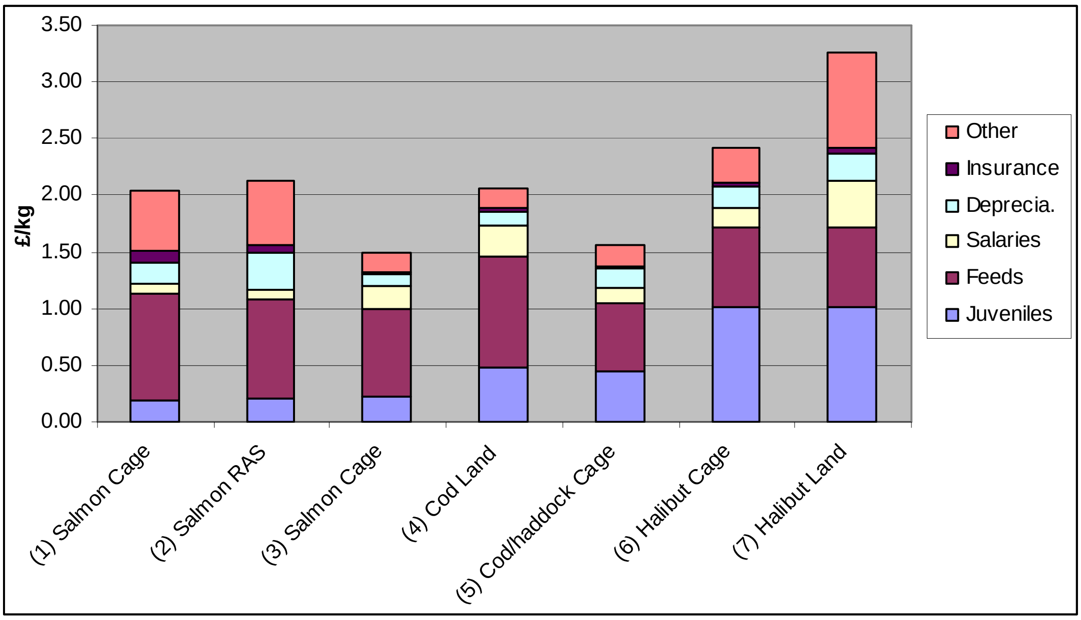


Table 5.3: Comparison of the power installed in the model studied and in an installed similar RAS for smolt hatchery

	RAS	**Model**	**Smolt**
Power installed	kW/m^3 (rearing volume)	0.048	0.049 *
	kW/t (maximum biomass)	0.80	0.70 *

** A. MacLean, pers. com.*

Direct costs are similar for cage and RAS model and account for about 70 % of OC. Energy and oxygen requirement for RAS are comparatively low and compensate for well-boat rental. Therefore, the production costs of both systems are similar. The relative costs of the models developed are realistic while the total costs are probably on the high range with regards to those authors. However, with a sales price slightly under £2.0/kg in July 2003, market prices were said to be under breakeven price for the majority of producers (*Intrafish, December 2003*).

Investment decision

First characteristic of the RAS is the need for a capital twice as high (Table 4.1), therefore, investment capacity and confidence in the system need to be high for investors. A high equity has the potential to consistently reduced financial charges from money borrowing (Table 4.8) to finally improve cash flow. For salmon grow out, RAS is economically viable at present market price (Table 4.6) but setting a cage farm in a medium exposed site is more competitive if the premium prices on RAS sales is low (+3.2 %). In that case, RAS profitability ratios are under levels often required by investors (SRR < 25 %, Pay-back > 4 years, IRR < 10 %). Those financial characteristics together with the confidence required for a large-scale pioneer aquaculture project explain the absence of such a system in Scotland and probably in the world.

If environmental costs were included in production costs, the profitability of salmon cage aquaculture would be similar than the one of the RAS. Nevertheless, cage systems would still suffer from environmental interactions and uncertainty of their evolution to become comparatively non-competitive.

If we off-set risks inherent to pioneer project and assume good design and functioning, as it could really be for a 200 t system (maximum biomass in a grow-out system), 70 % recycling, to rear the well-known Atlantic salmon species, risks appears lower than for a cage system. Moreover, environmental evolutions, such as so called “global warming” and increasing human pressure, are likely to increase risks for cage aquaculture (Aquaculture Risk (Management) Ltd., 2001) and degrade biological performance (survival, FCR…). Cage system is well-known and developed, the window for further improvement in management and cost-efficiency is reduced. Environmental costs are unlikely to be fully included but legislation will evolve. Industry extension is likely to be restricted and tax for organic discharge at sea introduced in order to promote investment for a clean industry. On the other side, capital cost for RAS items may be reduced with an increasing market, experience gain in design while system management may also improve from experience. The relative competitiveness of both systems will be closer and closer with years while the greater security of outputs and related prevision capacity may compensate for slower return and higher investment.

Beyond those forecasted modifications in the aquafarming Environment, a recirculating salmon grow-out system has the potential for high rewards, characteristic of pioneer project. As shown in figure 4.10 and 4.11, a premium price of 14.1 % is required to reach similar profitability, then any increase gives a greater competitiveness to the RAS system. This can be achieved firstly by the location of the farm closer to the market, even if the RAS site needs sea proximity and fresh water availability. In that way, the cost of transport to the final consumer can be reduced giving a greater margin to the producer thanks to integration of the production (processing). The continuity of output from an identified origin gives greater freshness and traceability, significant assets for a quality product, but also the opportunity to obtain better sales contracts and reach smaller quality retailers while reducing sales intermediary. Environmental respect and sustainability of the system are also significant advantages recognize by many consumers nowadays. The public is becoming aware of the flaws of traditional aquaculture industries; part of them would pay premiums for a Quality product thanks to communication, marketing and retails organization. Higher density in the RAS system could raise animal welfare protestations. However, the density of 50 kg/m^3 is under the maximum of 75 kg/m^3 claimed by animal welfare associations for fish rearing. Moreover, water quality and fish health has to be the primary consideration for welfare estimation.

This premium could also be reached in market where salmons are not traditionally reared (e.g.: Galicia; France) thanks to far greater freshness than imported salmon, reduced transport costs, wholesalers margins exclusion and support of a new locally reared species. This RAS system extends the geographic area for salmon aquaculture, however, this is hardly feasible without the development of a smolt hatchery for eggs incubation in this new area. The scale of the RAS would require a small hatchery having nevertheless an economical scale.

Finally, the RAS designed could be a specific tool required to legally reared Transgenic Atlantic Salmon (TAS). TAS is currently produced by A/F Protein Inc. (Waltham, MA) which hopes to supply broodstock (Hallerman).This modified strain is said to grow up to four to six times faster than non-transgenic salmon [*wild*] to reach market size in 18 months. Therefore, TAS is claimed to be a realistic way to diminish the pressure against wild stocks and increase the world's food supply (IFCNR, 2003). However, upon many fears and criticisms, ecological and consumer safety are the 2 well-known principal issues; a growing public seems to fear about genetically modified foods in Europe, US and Asia (Chern & Rickertsen, 2002). As a result, main producer associations around the world ban the rearing of TAS (Scottish Quality Salmon, 2000; International Salmon Farmers Association, 2000 IN Marine GEOs), some until further improvements or scientific data for safety and approval by legislation (Washington Fish Growers Association, 2000; British Columbia Salmon Farmer Association, 2001 IN ISES, 2001). TAS is probably not a solution for the industry but choices of individual farmers depend upon legislation which may accept TAS rearing in some country and in particular conditions. A legal requirement for TAS production in the future may probably be to highly confine the stock. RAS system may be proposed to such investors, even if TAS improved growth in such a system is not defined.

CONCLUSION

With regards to results obtained, a complete technical design and financial analysis appears necessary to confirm precisely results obtained. A risk analysis involving opinion of several professionals among the industry, together with a survey of available sites, environment and legislation modifications would be ideal to precise the future potential of salmon RAS. The development of a pilot-scale RAS for salmon grow-out would be ideal to assess performances even if the RAS in place for smolt rearing (freshwater) is a good preliminary pilot. Organic waste management requires a complete comparative study to define the optimal option. Investment decision would be dependent upon the feasibility to obtain a premium price of 15 % and/or to minimize production cost at consumer level. Market studies are required to asses' consumer willing to pay for quality, traceability, environmental respect as to assess consumers attitudes to RAS (e.g. welfare issues). The added cost of communication, marketing and specific sales path has to be assessed to define the price structure of salmon RAS at consumer level and compare it to potential premiums.

Multinational aquaculture companies are more likely to get the investment capacity required for such a system but their global organization reduced management cost of traditional system at various levels, particularly from human resources (e.g. 1 health manager for 1 region), processing and sales management (e.g. 1 processing center and 1 raw product from several farms). Recirculating system and product management would require investment in new skills and development of new paths required anyway by a newcomer. Investment in a real solution, asked by legislative bodies and the society, would be a proof of the investor commitment for a clean industry improving the image of the whole company and giving the opportunity to lead the way to salmon production diversification.

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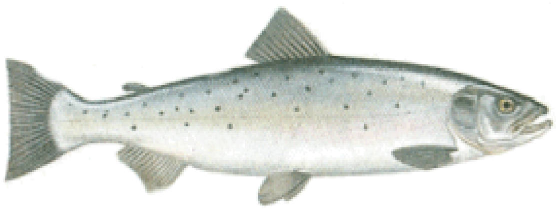
APPENDIX A Atlantic salmon presentation

Classification



Phylum:	Chordata
Subphylum:	Vertebrata
Class:	Actinopterygii
Order:	Salmoniformes
Family:	Salmonidae
Species:	Salmo salar

Geographic Range

The Atlantic salmon is native to the North Atlantic Ocean, from the Arctic Circle to Portugal, from Iceland and southern Greenland, and from the Ungava region of northern Quebec (Scott and Crossman, 1973). Being anadromous, young developpe in coastal rivers and streams while adult grow at sea and return to its native river to spawn.

Physical Description

The typical size range from 2 to 10 kg with an average between 4.5 and 5.5 kg (50-100 cm).

The adult Atlantic salmon is a graceful fish, deepening rearward from a small pointed head to the deepest point under the dorsal fin, then tapering to a slender caudal peduncle which supports a spreading and slightly emarginate caudal fin. Atlantic salmon are distinguished from the Pacific salmon because they have fewer than 13 rays in the anal fin. Their mouth is moderately large. The shape, length of head, and depth of body vary with each stage of sexual maturity.

The color varies with stage: From the pigmented bars of the "Parr", the smolt and adults are silvery with , at sea, shades of brown, green, blue and black spots. Spawners are bronze-purple then become dark after spawning as "Kelt" (Eddy and Underhill, 1974; Scott and Crossman, 1973).

Reproduction

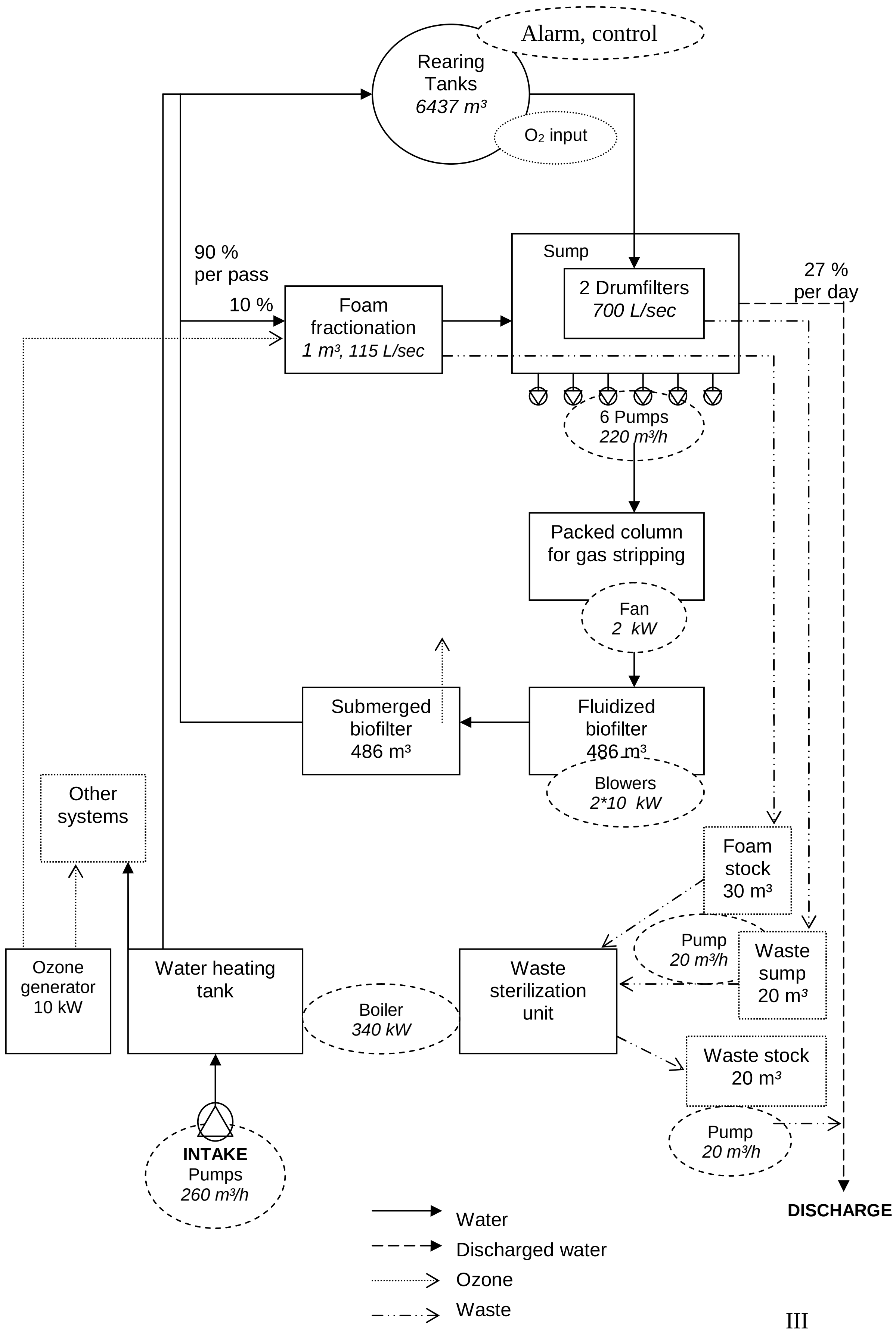
Wild Atlantic salmon spawn in October / November and the reproduction may take one or several weeks. Each female spawn several times an average of 1500 eggs per kg of body weight for a total of 3000-4000 eggs. The female choose the nesting site, usually a gravel-bottom and digs the nest. Eggs released and fertilized are buried at a depth of about 12 to 25 cm. Eggs are pale orange, large, spherical, and adhesive for a short time. After several spawns, spawners are exhausted, some die after spawning but many survive to spawn a second time after the next winter at sea.

Hatching of the eggs usually occurs in April, the yolk sac is absorbed in May or June and the young emerge. The alevins remain in fresh rapid water until they are about 65mm long and become parr. At 12 to 15cm they become smolt and are ready to go to sea. Salmon grow rapidly while at sea. Some may return to the river to spawn after one year at sea, as "grilse," or may spend 2 years at sea, as "2 sea-year salmon" (Scott and Crossman, 1973).

Food Habits

Young Atlantic salmon in streams eat mainly the larvae of aquatic insects but also terrestrial insects. When at sea, salmon eat a variety of marine organisms: Plankton, amphipods, decapods. Larger salmon eat a variety of fishes (herring, alewives, smelts, capelin,…). Prior to spawning, salmon cease to feed; they do not eat after they re-enter fresh water to spawn. (Bigelow, 1963).

APPENDIX B **RAS diagram**



APPENDIX C1 **CAGE MODEL** Annual production (1000 T I

Volume (m3) 70 440 m3

Technical specification	CAPITAL COSTS Item	type	Cost (£)	Quantity Phase1	Ph2	Total	Price Phase 1	Phase 2	Total (£)	Depreciation Period (y.)	Residual Value (£)	Value (£/y)
	pre-installation											
	Site detection (h)	FCC	15	90	0	90	1350	0	1350			
	Env. assessmen	FCC	5000	1	0	1	5000	0	5000			
	Build permit	FCC	750	1	0	1	750	0	750			
	Legal fees	FCC	7500	1	0	1	7500	0	7500			
	Design fees	FCC	2000	1	0	1	2000	0	2000			
	Land (m2)	VCC	20	1050	0	1050	21000	0	21000			
	Strip vegetation (	VCC	45	1050	0	1050	47250	0	47250			
	Remove top soil	VCC	3	910	0	910	2730	0	2730			
	Prepare founds f	VCC	30	910	0	910	27300	0	27300			
Concrete 910 m2, 100 mm, pla	Foundation (m3)	VCC	100	91	0	91	9100	0	9100			
	site/system costs											
Circum.96 m, 3 rings, 400mm,	Net pen	SVCC	22500	4	6	10	90000	135000	225000	5	0	45000
Circum. 96m, mesh size 9.5 m	Net	SVCC	15000	4	6	10	60000	90000	150000	4	0	37500
Circum. 96m, mesh size 22 mn	Net	SVCC	7500	4	6	10	30000	45000	75000	4	0	18750
Multipoint, with marker buoys	Mooring system	SVCC	11000	4	6	10	44000	66000	110000	6	0	18333
	Other……	SVCC	2500	1	1	2	2500	2500	5000	5	0	1000
	Husbandry											
Individual counter	Counter	SVCC	5000	2	2	4	10000	10000	20000	5	0	4000
Vaki circular grader	Grader	SVCC	12000	1	0	1	24000	0	24000	6	2000	3667
Vaccum pump, 1 to 6000 g, 1 t	Fish pump	SVCC	15000	2	0	2	30000	30000	60000	5	3000	11400
Kames 13 mm	Tarpaulins	SVCC	7000	2	2	4	14000	14000	28000	5	0	5600
AKVASensor Biomass Estimat	Biomass estimat	SVCC	75000	1	0	1	75000	0	75000	6	8000	11167
Liftup 3 system	Mort. collecteor	SVCC	12000	4	4	8	48000	48000	96000	6	0	16000
	Other……	SVCC	5000	1	0	1	5000	0	5000	4	0	1250
	Management											
4" mesh, S=346 m2, 0.29 £/m2	Predator net	SVCC	100	4	6	10	400	600	1000	5	0	200
Terecos, DSMS4	Seals scarers	SVCC	3000	2	2	4	6000	6000	12000	4	0	3000
Standard	Gas gun	SVCC	700	1	0	1	700	0	700	5	0	140
Oxy-therm., refractrometre	Water Quality co	SVCC	752	1	0	1	752	0	752	5	0	150
	Other……	SVCC	5000	1	0	1	5000	0	5000	5	0	1000
	Transport											
30 T, 17 m long, 7.5 knot, 80 L	Workboat	SVCC	170000	1	0	1	170000	0	170000	6	10000	26667
Standard	Voe boat	SVCC	30000	2	0	2	60000	0	60000	6	20000	6667
Standard	Dock	FCC	6000	1	0	1	6000	0	6000	8	0	750
Standard	Pickups/cars	SVCC	10000	1	1	2	10000	10000	20000	6	1000	3167
Standard	Trailer work boat	SVCC	5000	1	0	1	5000	0	5000	6	500	750
Standard	Trailer Voe boat	SVCC	3000	2	0	2	6000	0	6000	6	500	917
	Cleaning											
Standard	Pressure net wa	SVCC	1000	1	0	1	1000	0	1000	5	0	200
Standard	Net drying frame	SVCC	5000	1	0	1	5000	0	5000	8	0	625
	Facilities											
RH 3000 multifeeder Convertib	Barge (+feeder)	SVCC	548000	1	0	1	548000	0	548000	8	10000	67250
Prefab. building, insul. 100 m2	Office, accomod	FCC	12000	1	0	1	12000	0	12000	20	0	600
Various	Office & accomo	FCC	4000	1	0	1	4000	0	4000	10	0	400
250 m2	Workshop	FCC	11000	1	0	1	11000	0	11000	20	0	550
various	Workshop eqt	FCC	3000	1	0	1	3000	0	3000	10	0	300
220 m2, gravel 80 mm	Parking	FCC	123	1	0	1	123	0	123	20	0	6,15
Basic truck bitumen, 100 m	Road	FCC	50	100	0	100	5000	0	5000	20	0	250
	Connection to se	FCC	600	1	0	1	600	0	600	20	0	30
	Subtotal						1416055	457100	1873155			166702
	CC contingency (%)					10	141605,5	45710	187316		10	16670
	TOTAL CC						1557661	502810	**2060471**			183372
	TOTAL CC/tonne								2060			183,37

APPENDIX C2 **RAS** Annual produc 1000 T **II**

Volume (m3) 8195 m3

Technical specification	CAPITAL COSTS			Quantity			Price			Depreciation		
	Item	type	Cost (£)	Phase1	Ph 2	Total	Phase 1	Phase 2	Total (£)	Perioc	Residual	Value
	pre-installation									(y.)	value (:	(£/y)
	Site detection	FCC	15	70	0	70	1050	0	1050			
	Build permit	FCC	500	1	0	1	500	0	500			
	Legal fees	FCC	5000	1	0	1	5000	0	5000			
	Design fees	FCC	5000	1	0	1	5000	0	5000			
	Land	VCC	20	13000	0	13000	260000	0	260000			
	Strip vegetation(	VCC	20	8000	5000	13000	160000	100000	260000			
	Remove top soil	VCC	3	5000	5000	10000	15000	15000	30000			
	Excavation (m3)	VCC	30	1000	0	1000	30000	0	30000			
Concrete, 100 mm, placed	Foundation	VCC	90	1480	950	2430	133200	85500	218700			
	site/system costs											
15*10*3, vol = 450 m3, con	Tank water stock	SVCC	156	1	0	1	156	0	156	10	0	16
1287 m3; Diam=20 m; Dept	Tanks G	SVCC	30000	5	10	15	150000	300000	450000	8	0	56250
236 m3; Diam120 m; Depth	Tanks P	SVCC	17000	2	0	2	34000	0	34000	8	0	4250
700 L/sec, 40 micron; 5.8*2	Drumfilter G	SVCC	60000	2	4	6	120000	240000	360000	6	0	60000
180 L/sec, 40 micron; 5.65*	Drumfilter P	SVCC	24500	2	0	2	49000	0	49000	6	0	8167
111 L/sec; 1*1 m	Foam fract. G	SVCC	5500	1	2	3	5500	11000	16500	6	0	2750
35 L/sec, 0.5*0.5 m	Foam fract. P	SVCC	2500	1	0	1	2500	0	2500	6	0	417
30 m3, Diam =3.6 m; Depth	Tank foam	SVCC	1000	2	2	4	2000	2000	4000	6	0	667
486 m3, Diam=14.4 m; Dep	Biofilter Fluid. Ta	SVCC	22000	1	2	3	22000	44000	66000	8	0	8250
131 m3, Diam = 9.2 m, Dep	Biofilter Fluid. Ta	SVCC	11000	1	0	1	11000	0	11000	8	0	1375
486 m3, L = 20m, w = 8.1m	Biofilter Subm. T	SVCC	22000	1	2	3	22000	44000	66000	8	0	8250
131 m3, L = 11m, w = 6, de	Biofilter Subm. T	SVCC	11000	1	0	1	11000	0	11000	8	0	1375
405 m2/m3 and 135 m2/m3	Biofilter media G	SVCC	288	617	972	1589	177696	279936	457632	20	137290	16017
900 m2/m3	Biofilter media P	SVCC	342	309	486	795	105554	166018	271572	20	81472	9505
Tank: 5*5*2, vol= 50 m3, co	Ozonation systei	SVCC	42000	1	0	1	42000	0	42000	6	4200	6300
tank 28 m3	Oxygen system i	SVCC	25000	1	0	1	25000	0	25000	6	0	4167
See text	Co2 and pH cont	SVCC	1500	2	2	4	3000	3000	6000	4	0	1500
See text	Monitor/alarm	FCC	32000	1	0	1	32000	0	32000			
Standard	Ventilation	SVCC	500	3	2	5	1500	1000	2500	6	0	417
10 kW	Blower	SVCC	3000	4	4	8	12000	12000	24000	6	0	4000
Total	System C	SVCC	40000	1	0	1	40000	0	40000	6	0	6667
	Other……	SVCC	5000	1	0	1	5000	0	5000	5	0	1000
	Pumps/intake											
2 pipe, 300 m diameter, 20(	Intake system	SVCC	25000	1	0	1	25000	0	25000	10	0	2500
260 m3/h, 11 kW, head: 10	New water	SVCC	2000	1	0	1	2000	0	2000	6	0	333
500 m3/h, 22 kW, head: 4m	System G	SVCC	10630	8	16	24	85040	170080	255120	6	0	0
220 m3/h, 5.5 kW, 4m	System P	SVCC	2025	6	0	6	12150	0	12150	6	0	500
15L/min, 1.5 kW	Waste	SVCC	150	2	0	2	300	0	300	4	0	3750
	Husbandry											
Pneumo., 4 hoopers, 6T/h,	Feeders & silos	SVCC	40000	1	0	1	40000	0	40000	6	0	6667
Individual counter	Counter	SVCC	5000	2	2	4	10000	10000	20000	6	0	3333
Vaki circular grader	Grader	SVCC	12000	1	0	1	12000	0	12000	6	0	2000
Vaccum pump, 1 to 6000 g,	Fish pump	SVCC	15000	3	1	4	45000	15000	60000	5	0	12000
AKVASensor Biomass Estir	Biomass estimat	SVCC	75000	1	0	1	75000	0	75000	6	0	12500
	Other……	SVCC	5000	1	0	1	5000	0	5000	5	0	1000
	Security											
Standard	Barrier	SVCC	20	0	380	380	0	7600	7600	8	0	950
Standard	barbed wire	SVCC	0,11	0	714	714	0	79	79	8	0	10
	Waste treatment											
40 m3, PVC	Tank stockage	SVCC	1500	2	0	2	3000	0	3000	10	0	300
12 T/day, to 80 degree C	Unit installed	SVCC	15000	1	0	1	15000	0	15000	6	0	2500
concrete rings, 500 m, 300	Pipe discharge	SVCC	25000	1	0	1	25000	0	25000	10	0	2500

	Transport												
Standard	Pickups/cars	SVCC	10000	1	1	2	10000	10000	20000	6	1000	3167
33 T, 2 trailers, 16 m long,	Truck	SVCC	28850	1	0	1	28850	0	28850	6	2000	4475
	Heating and cooling											
340 kW, gas, 5 central poir	Water Boiler	SVCC	24000	1	0	1	24000	0	24000	10	0	2400
Standard	Cooler system	SVCC	14000	1	0	1	14000	0	14000	10	0	1400
	Cleaning						0	0	0			
Standard	Pressure net wa:	SVCC	1000	1	0	1	1000	0	1000	5	0	200
	Facilities											
Lightproof, insulated, 20 m	Dome cover	SVCC	14000	5	10	15	70000	140000	210000	10	0	21000
Lightproof, insulated, 10 m	Dome cover	SVCC	3400	2	0	2	6800	0	6800	10	0	680
Prefabricated building, insu	Building technic+	FCC	60000	1	0	1	60000	0	60000	20	0	3000
Various	Workshop eqt	FCC	3000	1	0	1	3000	0	3000	10	0	300
2 office+1 meeting = 50 m2	Office & accomo	FCC	13200	1	0	1	13200	0	13200	20	0	660
Various	Office & accomo	FCC	5000	1	0	1	5000	0	5000	10	0	500
Surf=220 m2: 20*10m	Parking	FCC	123,2	1	0	1	123,2	0	123,2	20	0	6
Basic Truck Bitumen, 10 m	Road	FCC	50	10	0	10	500	0	500	20	0	25
	Connection to se	FCC	100	1	0	1	100	0	100	20	0	5
	Subtotal						2073720	1656212	3729932			289999
	CC contingency (%)			10			207372	165621	372993		10	29000
	TOTAL CC						2281092	1821833	**4102925**	100		318999
	TOTAL CC/tonne								**4102,9**			319

APPENDIX D

CAGE MODEL

OPERATING COSTS				
Item	Type	Cost (£)	Quantity	Total (£)
Direct costs				
Fry (Ind)	VOC	0,8	244500	195600
Feed (T)	VOC	710	1318	935723
Chemicals	VOC	10 000	1	10000
Human resources				
Manager	FOC	24000	1	24000
Workers	SVOC	16000	3	48000
Secretary	SVOC	13000	1	13000
External services	SVOC	15000	1	15000
Helicopter rental	SVOC	1200	2	2400
Well-boat rental (£/day)	SVOC	5000	3	15000
Well-boat rental (£/day)	SVOC	5000	44	220000
Net service (£/net)	SVOC	850	16	13600
Insurance cost	VOC			105768
Energy				
Electricity	VOC	0,032	87600	2786
Fuel	VOC	0,8	2112	1690
Misc power	VOC	10%		448
Other				
Telecom, etc	FOC	1000	1	1000
Maintenance	SVOC	2% CC/yr	0,02	41209
Business rates	SVOC	2% CC/yr	0,02	41209
Sub total				1686433
OC contingency (%)	FOC	10% CC/y	0,1	168643
TOTAL OC				1855076
OC/tonne				1855

RAS

OPERATING COSTS				
Item	Type	Cost (£)	Quantity	Total (£)
Direct costs				
Fry ('000)	VOC	0,8	258900	207120
Feed (T)	VOC	710	1236	877834
Chemicals	VOC	10000	1	10000
Oxygen (/kg)	VOC	0,11	490718,47	53979
Human resources				
Manager	FOC	24000	1	24000
Workers	SVOC	16000	3	48000
Secretary	SVOC	13000	1	13000
External services	SVOC	15000	1	15000
Insurance cost	VOC			66365
Energy, auxiliaries				
O2 tank rental	VOC	25000	1	25000
Electricity	VOC	0,0306	3132576	95857
Natural gaz	VOC	0,0101	1130259	11416
Fuel	VOC	0,8	3564	2851
System C	VOC			21454
Misc power	VOC	5%		5506
Other				
Telecom, etc	FOC	1000	1	1000
Maintenance	SVOC	2% CC/yr	0,02	82058
Business rates	SVOC	2% CC/yr	0,02	82058
Sub total				1642500
OC contingency	FOC	10% CC/y	0,1	164250
TOTAL OC				1806750
OC/tonne				1807