Real options under technological uncertainty: A case study of investment in a post-smolt facility in Norway

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Marine Policy, Volume 88, February 2018, Pages 158-166

https://doi.org/10.1016/j.marpol.2017.11.020

March 23, 2018

Abstract

This paper evaluates the optimal timing to undertake an investment in a post-smolt production facility under both profit and technology uncertainty, using a real options approach. Two multi-factor stochastic models are developed to distinguish between the technological innovations that reduce the investment cost and increase the efficiency of the production process. The results indicate that by relying on traditional capital budgeting methods the salmon farming companies may undervalue sensible investment opportunities, such as post-smolt production. Additionally, it is show that the investment strategy of the salmon farming company is greatly influenced by the way the benefits of the technological innovations affect the firm. A farmer has stronger incentives to delay investment when the expected benefits of technological innovations are associated with the future investment cost reduction.

1 Introduction

The Norwegian salmon farming industry is currently facing major obstacles to future growth. Global demand for salmon is increasing, but due to biological challenges, the supply is constrained (Asche *et al.*, 2011; Brækkan and Thyholdt, 2014). The main reasons are the exposure of the companies to several operational risk factors, as well as the regulations enforced by the government. The operational risks are mainly associated with the sea water period, when the fish is most vulnerable to sea lice and diseases, and is more likely to escape from the cages (Torrissen *et al.*, 2013; Asche *et al.*, 1999). As a result of the rapid increase in the level of sea lice over the recent years, the salmon farming industry is facing significant costs, stemming from delousing the fish and disease treatment (Costello, 2009; Abolofia *et al.*, 2017). In addition, capacity expansion of the farms is limited by the lack of fjord space, and the environmental considerations related to its negative influence on the welfare of wild salmon (Liu *et al.*, 2011).

Due to these challenges Norwegian authorities impose stringent regulations on salmon farmers. The production in the industry is currently controlled by awarding companies farming licenses. Each license granted to a salmon farmer gives the right to keep a certain maximum volume of fish at sea at all times, referred to as the maximum total biomass (MTB) (Asche and Bjørndal, 2011). Due to the reluctance of the authorities to allow future growth in the industry, the supply of these licenses is scarce (Christiansen and Jakobsen, 2017). Therefore, both salmon farmers and the suppliers are actively working on developing ways to improve fish health and increase production without violating regulations. In 2015, the government introduced a new measure to stimulate innovation activity in the industry. The companies that commit to test new technological solutions that may help in coping with the industry challenges are now able to apply for special "development" licenses, that can be converted into regular commercial licenses upon fulfilling certain criteria. This has stimulated additional investments aimed at developing new measures to deal with the biological problems, so that the industry can continue to grow.

One of the measures considered is post-smolt production, which involves growing the salmon larger in a protected environment before moving it into traditional sea cages. By shortening the seawater production period, accumulated mortality and need for expensive medical treatments are reduced (Asche and Bjørndal, 2011). Moreover, replacing fish at slaughtering weight by post-smolt increases the biomass utilization. As post-smolt production has potential to increase both profits and fish welfare, it is expected to be beneficial from both an economic and ethical perspective (Martins *et al.*, 2010). The technology is, however, still in a development phase, and many of its benefits are expected rather than certain. As post-smolt production is at an early stage in terms of R&D, there is a high level of uncertainty related to important factors such as the cost and performance level of the technology and its influence on the fish welfare, in addition to uncertainty in operating profits (Terjesen *et al.*, 2013).

The primary methods used by companies to evaluate projects are internal rate of return (IRR) metric or net present value (NPV) criterion (see, e.g., Bunting and Shpigel, 2009; Liu *et al.*, 2016; Whitmarsh *et al.*, 2006). However, when there is high uncertainty related to an investment, traditional methods fail to correctly value the investment opportunities (Dixit and Pindyck, 1994). This is because traditional capital budgeting methods take into account only the downside of uncertainty, disregarding its upside potential. In such situations one should use real options valuation (ROV), which allows to treat uncertainty correctly.

This paper investigates whether real options analysis can uncover additional value compared to traditional capital budgeting methods when evaluating an investment in a post-smolt facility under technological uncertainty. In particular, it is explored how the combination of technology and profit uncertainty affects the optimal investment strategy by developing multi-factor models on the forefront of real options theory. Unlike the traditional methods, the models proposed in our study capture the upside potential of the uncertainty embedded in post-smolt production. The models' underlying assumptions and input parameters are chosen in close collaboration with both biological researchers and representatives from the industry. Our results suggest that real options valuation uncovers significant excess value compared to the traditional methods, and, thus, has the ability to improve the decision making process for a wide range of the investment problems in the salmon farming industry.

The importance of recognizing technology development as a source of uncertainty in real options analysis was emphasized by Farzin *et al.* (1998). They use real options analysis to determine the optimal timing of technology adoption under a stochastic innovation process, and show that even in the absence of other kinds of uncertainty, e.g. uncertainty about market conditions, a firm's optimal timing of adoption is greatly influenced by technological uncertainties. Among the recent contributions that account for both technological and profit uncertainty is Huisman and Kort (2004) and Murto (2007). The latter focuses on the conjoined effects of two factors affecting technological uncertainty, i.e. the arrival rate of technological improvements and the investment cost reduction factor, on the timing of the investment decision. In this paper follows the approach of Huisman and Kort (2004), and provide insights in how technology and profit uncertainty affect the optimal investment strategy in post-smolt production. Similarly to Murto (2007), technological uncertainty is modeled as an arrival of innovation that either reduces the investment cost or increases production efficiency.

Several academic studies on aquaculture has focused on economics of salmon farming and, in particular, production efficiency (Asche *et al.*, 2013). Recent contributions indicate that there is a scope of improvement in technical efficiency in the industry (Asche and Roll, 2013), and emphasize that innovation process in the industry has lead to a significant productivity growth (Asche *et al.*, 2016). Due to the current boom in R&D activity in the industry, there is a growing demand for studies analysis efficiencies of available technologies, and, in particular, post-smot production. Sandvold and Tveterås (2014), for example, identify how the change in technology has influenced the productivity growth in smolt production from 1988 to 2010. They find that technological innovation has led to a reduction in unit production costs. Another contribution that directly addresses a problem of efficiency of technologies used in smolt production is Sandvold (2016). This study uncovers significant inefficiencies in smolt production technology, however at the same time indicates the presence of a learning-by-doing effect. This paper builds upon these insights by allowing for the stochastic development of technology process.

The remainder of this paper is organized as follows. In Section 2 elaborates on the motivation behind post-smolt production. Section 3 introduces two multi-factor real options models that evaluate the optimal timing to undertake an investment in a post-smolt production facility under both profit and technology uncertainty. In Section 4 presents a post-smolt case study, and quantify the parameters. In Section 5 a sensitivity analysis with respect to the input parameters is conducted. Section 6 concludes. The proofs of propositions and the description of the numerical algorithm are presented in the appendices.

2 Post-smolt production

Until 2012, post-smolt production was not an option for Norwegian farmers, as government regulations stated that hatchery-reared salmon should not have an individual weight exceeding 250 grams before being set into traditional sea cages. As of 2012, however, the Ministry of Fisheries awards holders of hatchery permits licenses to produce smolt with an individual weight exceeding this limit up to 1000 grams in closed or semi-closed tanks on land or in the sea, under certain conditions (Department of Fisheries and Coastal Affairs, 2011). This made post-smolt production possible, and is by many industry actors and researchers highlighted as a possible solution to the market imbalance problem. Post-smolt production provides several benefits.

As the smolt is kept longer in a protected environment before being set into traditional sea cages. In this way the time spent in seawater can be significantly shortened, for example from 15-18 to 9-12 months depending on the performance of a post-smolt facility. This leads to a reduction in the accumulated mortality, as the seawater is the most lice and disease prone environment in the production cycle (Asche and Bjørndal, 2011). In traditional salmon farming, as much as 20 percent of the fish die before reaching slaughtering weight. In comparison, several studies show that it is possible to achieve mortality rates of 1-2 percent under optimal conditions in post-smolt facilities (Ytrestøyl *et al.*, 2017; Davidson *et al.*, 2017). Given the regulations on sea lice, the farming companies could expect to save at least one delousing per production cycle, which according to the Norwegian company SalMar can cost around NOK 300,000 per cage[1]. Keeping the fish in a closed environment also eliminates the risk of escapes during the first phase of the production cycle. Finally, a larger growth rate and generally better fish welfare can be achieved by controlling the rearing environment, and in particular water quality (Summerfelt and Vinci, 2009).

Even though there are strong arguments for post-smolt production in terms of reducing production risk and improving the production efficiency, it still involves significant technological uncertainty that is not inherent in traditional salmon farming. The technology used in post-smolt production is in a development stage and its performance and reliability are yet to be proved on a commercial scale. Additionally, the cost of the equipment required for post-smolt production is expected to change due to technological improvement. Finally, it is currently more expensive to produce salmon in closed systems compared to traditional sea cages (Liu *et al.*, 2016). Note, however, that there is a potential for productivity growth and cost reduction as the systems become more commonly used due to learning effects, and as the technologies develop over time (Summerfelt *et al.*, 2016). Currently, there are two competing post-smolt production technologies. According to the industry representatives, Recirculating Aquaculture Systems (RAS) is the industry's preferred technology, as opposed to flow through systems. There are several suppliers of RAS technology, such as AKVA group, Kruger Kaldnes and Billund Aquaculture, creating high competition for the few available contracts in the market. Recirculating Aquaculture Systems are closed-loop production systems for land-based fish farming. The system recycles about 99.5 percent of the water in the system. This enables large-scale fish farming on land with minimal water usage. The main advantage here is the ability to maintain optimal water quality with less effort than if the water was not recycled (Kristensen *et al.*, 2009). Ensuring high water quality is beneficial in terms of increased growth. The main disadvantage, however, is that the technology needed to install a post-smolt facility is fairly new, and yet to be proven on a commercial scale. As a result, there is high uncertainty related to the costs and performance of the current technology, as well as the introduction of any new and improved technology (Ngoc *et al.*, 2016). The aquaculture firms are, therefore, still reluctant to undertake investments (Martins *et al.*, 2010).

[1]This is approximately equal to USD 35 400 per cage. The exchange rate for 1 Norwegian Krone is approximately 0.118 USD in June 2017.

3 Models

This section presents the approach to analyze the investment decision of the salmon farming company. Consider a risk neutral firm that has the possibility to undertake a single irreversible investment in a post-smolt production facility. If the salmon farming company chooses to invest at time t it faces a one-time, sunk cost denoted by K_t. After investment the company starts generating profits instantaneously, i.e. there is no time lag in setting up the facility (a similar assumption is made, for example, by Bernanke (1983) and Cukierman (1980)). The total annual profit of a salmon farmer is denoted by R_t, which is defined as a product of the unit profits and total annual quantity $R_t = \pi_t Q_t$. The unit profits, π_t, are assumed to be stochastic and follow a geometric Brownian motion (as in, e.g., Himpler and Madlener (2014)), such that

$$d\pi_t = \alpha_\pi \pi_t dt + \sigma_\pi \pi_t dZ_{\pi,t}, \quad (1)$$

where α_π represents the drift and σ_π is the volatility. Tax is neglected as it has a similar effect on both net present value and real options value, and will, therefore, not affect our ability to compare the results.

The technological evolution is assumed to be exogenous to the firm, as our case study focuses on a relatively small salmon farmer that does not have the resources to perform R&D. Two separate models are developed in order to isolate the effects of the different type of technological innovations, namely, the innovation that reduces the investment costs of the salmon farmer, and innovation that improves the efficiency of the post-smolt production equipment.

The first model focuses on the effect of investment cost reduction on the optimal investment strategy of the salmon farming company. It is assumed that this stems from a reduction of the suppliers' production costs. The competition among the suppliers of post-smolt technology is high, which entails downward pressure on selling prices. Therefore, this directly leads to a lower investment cost for the salmon farming company. In order to isolate this effect, it is assumed that the annual production quantity is constant, $Q_t = Q$, whereas the investment cost, K_t, declines over time. The arrival of an innovation reducing K_t is assumed to be Poisson distributed and always improve upon the best-available technology. Hence, the investment cost at any time is equal to

$$K_t = K_0 \phi^{N_t}, \quad (2)$$

where K_0 denotes the initial investment cost, N_t is a Poisson random variable with mean λt counting the number of innovations, and $\phi \in [0, 1]$ is a constant reflecting the size of the investment cost reduction. The investment cost reduction factor, ϕ, is defined such that a large value of ϕ represents a small innovation, while a small value implies a large innovation. Hence, a combination of a large

λ and a small ϕ corresponds to the case of frequent innovations with high reducing impact on the investment cost. This would result in the largest option value.

The second model isolates the impact of technological innovations that improve the efficiency of the post-smolt production equipment rather than reduce the investment cost. Therefore, it is now assumed that the investment cost is constant, $K_t = K$, whereas the innovation directly affects the revenues. The model accounts for such an innovation in two ways, i.e. by considering both large improvements and minor technological developments.

First, the introduction of a technological innovation is assumed to boost the total annual profits by a factor $\gamma \geq 0$, such that the annual profits will increase from $\pi_t Q_t$ to $\pi_t Q_t(1+\gamma)$. This corresponds to a large technological improvement. The arrival time of the innovation, τ_λ, follows an exponential distribution with intensity λ. As there is limited potential for improvement in this area, the innovation is allowed to arrive only once. According to industry experts, a large innovation improving the efficiency of the post-smolt production is likely to arrive in the form of research describing best-practice for operating a post-smolt facility. As there is a high degree of cooperation in the salmon farming industry when it comes to post-smolt R&D, information leading to significantly more efficient production will likely be shared between companies. It is, therefore, assumed that the improvement can be adopted at no cost, and that the benefit is gained regardless of investment timing. Reduced mortality is found to be the most probable outcome of improved production processes.

Second, the model accounts for minor technological developments by assuming that the production quantity, Q_t, is stochastic and follows a geometric Brownian motion with positive drift such that

$$dQ_t = \alpha_Q Q_t dt + \sigma_Q Q_t dZ_{Q,t}, \tag{3}$$

where the drift term, α_Q, represents small costless technological improvements allowing for a slight improvement in facility efficiency, and the volatility term, σ_Q, stems from oscillating mortality rates. This way the effect of the innovation is incorporated as a general steady increase in produced quantity resulting from continuous "learning by doing" in the industry with minor deviations that arise due existing inefficiencies (see, e.g., Sandvold (2016)). In general, Q_t is a discrete variable, but since a facility would produce at high volumes, quantity is modeled as a continuous process.

The models, henceforth referred to as Model 1 and Model 2, are solved using the approach in Dixit and Pindyck (1994), and extended by, among others, Huisman and Kort (2004) and Murto (2007). In particular, a real options valuation is applied to this problem, recognizing that the company holds a perpetual option to invest and accounting for the fact that it faces both an uncertain future profit flow, and uncertain technological evolution process. The intrinsic value of the option is treated as an approximate to the net present value given by a simplistic DCF analysis. The optimal strategy of a firm is defined in the form of the optimal investment thresholds that trigger the investment, and the optimal value function. In addition, the expected time needed to reach the optimal investment thresholds is estimated for both models using simulation procedures. The detailed derivations and the description of the methods are presented in the appendices[2].

4 Post-smolt case study

This section quantifies the input variables for evaluating an investment in a post-smolt production facility. Our case study is based on a medium-sized Norwegian salmon company. The company consists of 18 employees, and is run by one of two company founders. It owns seven farming licenses for salmon and trout, that are split between two locations, as well as their own hatchery. The farmer has ambitions to expand production over the coming years. One of the main investments under consideration is in a post-smolt facility, which to a large extent has been approved in terms of the biological aspects, but still needs to be justified from a financial perspective. The fact that the technology necessary to run a post-smolt farm is still in a research phase entails that relevant and proven information and data is not easily available. Many big companies are investing in test facilities delivered by different suppliers. They are facing different prices on the systems and related inputs from the suppliers, making them reluctant in what information they share with the general audience. Therefore, all the parameter values have been chosen in close cooperation with leading academics, business leaders and industry experts [3]. The results are summarized in Table 1.

[2]Appendix A for Model 1 and Appendix B for Model 2.

[3]The interviews were conducted with industry representatives from INAQ, SalMar, Marive Harvest, AKVA Group, Tjeldbergodden Settefisk, Nordea Markets, Steinvik Fiskefarm.

Parameter	Symbol	Model 1	Model 2
Investment cost	K	MNOK 50	MNOK 50
Discount rate	r	12%	12%
Innovation arrival rate	λ	0.2	0.2
Initial annual production output	Q	500 mt	500 mt
Quantity volatility	σ_Q	-	5%
Quantity drift	α_Q	-	1%
Initial unit profit	π_0	NOK 12.25	NOK 12.25
Profit volatility	σ_R, σ_π	25%	25%
Profit drift	α_R, α_π	2%	2%
Investment cost reduction factor	ϕ	0.95	-
Profit improvement factor	γ	-	0.1
Initial total annual profit	$R_{(t=0)}$	MNOK 6.125	MNOK 6.125
Initial benefit to cost ratio	p_0	0.1225	-
Combined growth rate	$\mu_{\pi Q}$	-	3%
Correlation	ρ	-	0

Table 1: Input parameters for the models summarized

The investment costs for the facility, K, are assumed to be MNOK 50. As a case study is performed on a relatively small company, the investment costs reflect that of a small post-smolt production facility. The number is based on information received from the Norwegian aquaculture technology provider AKVA Group and the Norwegian salmon farming company SalMar. The farmer under consideration owns the land needed to install the facility, and, therefore, does not incur the costs associated with the land lease or purchase. It is assumed that the equipment does not have to be renewed and, thus, the investment cost is assumed to occur only at the time of investment. In Model 1, K is a stochastic variable with the initial value of MNOK 50.

The discount rate, r, reflects the risk embedded in the project. The discount rate in salmon farming companies is typically set by the company board and assumed equal among all projects. These rates normally range from 8 to 10 percent depending on the size of the company. However, given the risk inherent in the project considered, the discount rate is set to 12 percent.

The case study evaluates a facility with an initial annual production Q of 500 metric tons of post-smolt. The individual post-smolt weight is set to 400 grams, which entails a production output of 1.25 million post-smolt. The specific fish weight is chosen based on advice from several of the largest salmon farming companies in Norway, including SalMar and Marine Harvest Group, who pointed out that the costs of land-based production increase fairly rapidly when surpassing a production weight of 400 grams.

Model 1 allows to isolate the effects of uncertainty in profit development and investment cost. Therefore, the quantity of post-smolt produced is assumed constant and equal to 500 tons annually throughout the model. Model 2 assumes that there is growth, α_Q, and volatility, σ_Q, in the production output. For this model, the growth rate is set to 1 percent annually. It is assumed that the volatility in the production output stems from oscillating mortality rates. The average mortality rate for traditional salmon farming in Norway varies between approximately 15 and 20 percent (Aunsmo *et al.*, 2013). The Norwegian salmon farming company Grieg Seafood was among the first to test post-smolt production in a RAS facility, and they have achieved a mortality rate of 2 percent in their most successful batches. However, as this is not an average and consistent rate, but merely the best case achieved in a small-scale research facilities, this would be an optimistic number to apply as model input. Therefore, the mean annual survival rate is set to 90 percent, and the standard deviation of Q to 5 percent.

There are three values related to unit profits, π, that need to be determined: (1) initial unit profit, π_0, (2) volatility in unit profits, σ_π, and (3) drift in unit profits, α_π. First, as most salmon farming companies considering post-smolt production aim to be self-sufficient, the usual method of calculating the price of the post-smolt is cost-based pricing with no mark-up. However, an investment in a facility can never be justified when the profit margin is constantly zero. The spot market for post-smolt exists mainly to serve companies' urgent demands for specific weight classes of post-smolt, caused by unexpected incidents of mass mortality. This creates market prices that are inelastic and highly volatile. Therefore, spot market prices cannot be used to determine initial unit profit. Experts advised that the post-smolt price should be set equal to the total production cost plus a margin. For the production cost the price of smolt at a specific weight is calculated. The price is the sum of a fixed cost of NOK 4.5 per individual and NOK 0.05 per gram of fish. This results in a cost of NOK 61.25 per kg. The margin used in the model is set to 20 percent, which corresponds to a selling price of NOK 73.5 per kg. The unit profit is then equal to NOK 12.25 per kg in the first year.

As already mentioned, it is assumed that the per unit profit of post-smolt production follows a geometric Brownian motion. In the long run the post-smolt price the salmon price should be correlated. Therefore, a volatility in the model is considered to be in the same range as the salmon price volatility. From January 1990 to October 2012, annualized volatility of monthly salmon prices have ranged from about 16 to 35 percent[4] (Asche *et al.*, 2015). Hence, volatility of the per unit profits is set to 25 percent, but perform a sensitivity analysis to test how a change in volatility affects the value of the

[4]Adjusted by the monthly trade volume.

investment opportunity. As the model considers a perpetual option, the per unit profits cannot grow faster than the overall economy in eternity, which grows at around 2-3 percent annually (Koller *et al.* (2010)). Additionally, as commodity prices often show a mean-reverting behavior in the long run and salmon closely resembles a commodity, the drift rate of the associated price should not be set too high. Therefore, the drift rate of the geometric Brownian motion representing per unit profits is set to 2 percent. This applies to both models presented.

If the investment was made today, the initial production volume would be equal to $Q = 500$ tons and per unit profit to $\pi_0 =$ NOK 12.25, hence the total profit in the first year of operation, denoted by $R_{(t=0)}$, is equal to MNOK 6.125, and the corresponding benefit to cost ratio, p_0, is equal to 0.1225.

The arrival rate of innovating technology in post-smolt production, λ, is set to 0.2. This would indicate an expected arrival every 5 years and applies to both models presented. An innovation is assumed to reduce investment cost by 5 percent (Model 1) and improve total annual profits by 10 percent (Model 2). The intuition behind using different innovation factors for the models is that only one innovation is allowed in Model 2, while there is no limit on the number of innovations (or Poisson jumps) that can occur in Model 1.

In Model 2 the correlation between quantity and unit profits, ρ, is set to zero due to the lack of data. The consequence of this assumption is that the growth rate becomes the sum of the growth rates of quantity and unit profits, that is 3 percent. Section 5 tests the sensitivity of the results with respect to this assumption.

5 Results

In order to identify if real options valuation can uncover additional value compared to NPV analysis, and to give intuition on how technology and profit uncertainty affect an investment in a post-smolt production facility, this section presents results of the case study, and sensitivity analyses.

5.1 Multi-factor model with stochastic profit and investment cost

This section presents the results of Model 1. Unless stated otherwise, the following values for the input parameters are used (see Section 4): $r = 0.12$, $\phi = 0.95$, $\sigma_R = 0.25$, $\alpha_R = 0.02$ and $\lambda = 0.2$. This set of parameters is henceforth referred to as the base case for Model 1. Figure 1 illustrates the value of the option to invest, $f_W(p)$, and the intrinsic value, $f_S(p)$, as a function of the benefit to cost ratio, $p = \frac{R}{K}$.

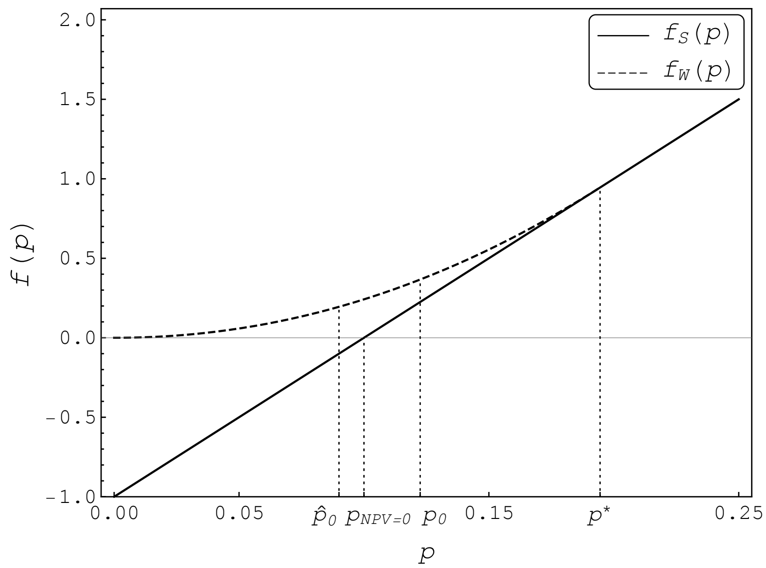


Figure 1: The value function of the firm .

The function $f_W(p)$ represents the ratio of the value of the investment opportunity to the investment cost. Similarly, the intrinsic value, $f_S(p) = \frac{p}{r-\alpha} - 1$, represents the net present value of the project relative to the investment cost. The intrinsic value line intersects with the horizontal axis at $p_{NPV=0}$, i.e. when $\frac{R}{K} = 0.1$, indicating that the traditional NPV analysis would suggest investing given that the first year's total annual profit is at least 10 percent of the investment cost. For the initial value of the benefit to cost ratio, $p_0 = \frac{R_{(t=0)}}{K} = \frac{6.125}{50} = 0.1225$, the NPV criterion suggests to undertake an investment immediately. Real options analysis, however, indicates that the optimal investment threshold is equal to $p^* = 0.1945$. For $p < p^*$, $f_W(p)$ is larger than the intrinsic value, $f_S(p)$, and the difference represents the value of the flexibility to delay the investment until the optimal investment threshold p^* is reached.

Furthermore, failing to correctly specify the initial value of the benefit to cost ratio may greatly influence the results. For instance, if the initial investment cost turns out to be larger due to incorrect assessment, the NPV analysis may suggest that the investment is never optimal. Note that in our case the farmer does not have to cover the costs for land lease. In many cases this advantage might not be present, and the investment cost for land based systems might be substantially higher (see, e.g., Zucker and Anderson (1999)). To illustrate this, $\hat{p}_0 = \frac{R_{(t=0)}}{K} = \frac{6.125}{67.5} = 0.091$ is displayed in Figure 1, which represents the today's benefit to cost ratio of the salmon farmer had the investment costs increased by 35 percent. In general, an increase in the investment cost by only MNOK 11.25 (or more) would lead the salmon farming company into rejecting the opportunity to invest forever, wheres the real options analysis shows that there exists a value of waiting with investment.

In what follows a sensitivity analysis is conducted in order to determine how changes in the values of the input parameters affect $f_W(p)$ and the threshold p^*. Table 2 below summarizes our main findings of the sensitivity analysis. The direction of the arrows in the table indicate the effect of an increase in the specific input parameter on the value of investment opportunity and the investment threshold.

Parameter	**Symbol**	$f_W(p)$	p^*
Investment cost	K	$\downarrow$	$\uparrow$
Innovation arrival rate	λ	$\uparrow$	$\uparrow$
Investment cost reduction factor	ϕ	$\downarrow$	$\downarrow$
Profit volatility	σ_R	$\uparrow$	$\uparrow$
Profit drift	α_R	$\uparrow$	$\downarrow$
Discount rate	r	$\downarrow$	$\uparrow$

Table 2: Effect of increase in input parameters on the value of $f_W(p)$ and on the investment threshold p^* in Model 1.

Evidently, an increase in the investment cost K, gives a lower value of the investment opportunity $f_W(p)$, and a larger investment threshold. This is because the salmon farming company demands a larger profit level to compensate for an increased investment cost. At the same, an increase in the initial investment cost decreases the initial benefit to cost ratio. As mentioned earlier, an increase or 22.5 percent or more is enough to yield a negative project NPV. Thus, a salmon farmer that relies on this criterion in its investment decision will reject the sensible business opportunities.

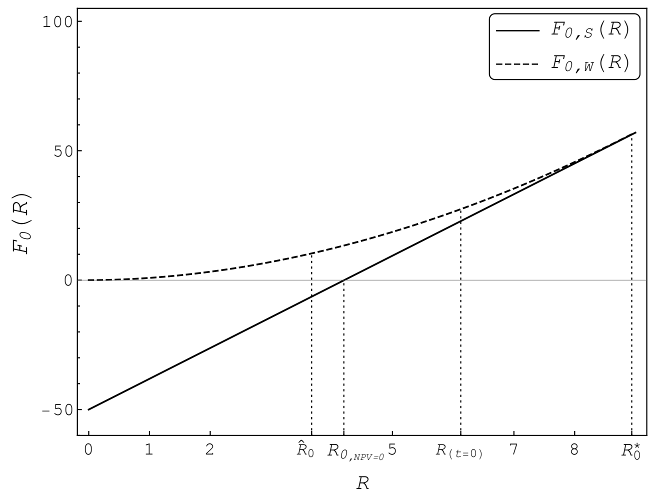
An increase in the innovation arrival rate λ leads to a larger option value, $f_W(p)$. This is intuitive, as a larger arrival rate of innovations reduces the expected investment cost, and, thus, increases the value of the investment opportunity, $f_W(p)$. Additionally, the investment threshold p^* increases with λ. This is because the larger λ is, the sooner the salmon farming company expects an investment cost reduction. As a result, it has stronger incentives to delay the investment. Similarly, a more significant investment cost reduction factor, i.e. a lower ϕ, decreases the expected investment cost, and, hence, increases the value of the investment opportunity. This results in a larger option value, $f_W(p)$, for lower levels of ϕ. A decrease in ϕ also leads to an increase in p^*, the salmon farming company has stronger incentives to delay investment, expecting a larger investment cost reduction. Thus, λ and ϕ have similar effects on $f_W(p)$ and p^*. In other words, the expectation of frequent but small innovations (high λ and high ϕ), and few but large innovations (low λ and low ϕ), increases the value of the investment opportunity, and, at the same time, creates more incentives to delay the investment.

Table 2 also shows that both the option value and the optimal investment threshold increase in the profit volatility, σ_R. This in line with classic options theory (see Dixit and Pindyck (1994)) as more uncertainty, all else held equal, should both increase the value of the investment opportunity but also make the salmon farming company more reluctant to invest in the project. An increase in profit growth rate, α_R, leads to a larger option value, together with a smaller investment threshold, p^*, as a larger profit growth rate increases the expected value of the project, and hastens the investment decision. A larger discount rate, in turn, reduces the expected value of the project. As demonstrated in Table 2, this implies that $f_W(p)$ and p^* decline with r. An large discount rate implies that the firm discounts its future payoffs more heavily. As a result the value of the opportunity to invest, $f_W(p)$, decreases. This also implies that the investment becomes less attractive, and the firm requires a higher benefit to cost ratio to invest. Numerical experiments indicate that both $f_W(p)$ and p^* are highly sensitive to α and r. Therefore, it is important for the salmon farming company to be precise when quantifying these parameters.

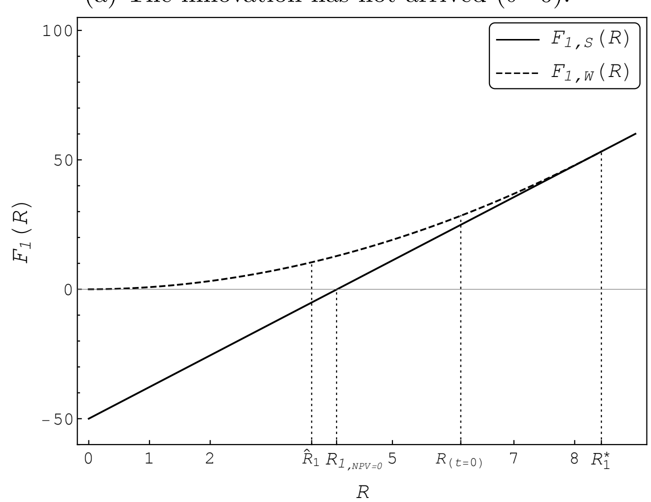
5.2 Multi-factor model with stochastic profit and quantity, and sudden arrival of an innovation

This section presents the results of Model 2. Unless stated otherwise, the following values for the input parameters are used(see Section 4): $r = 0.12$, $\tau = 0.1$, $K =$ MNOK 50, $\sigma_\pi = 0.25$, $\sigma_Q = 0.05$, $\alpha_\pi = 0.02$, $\alpha_Q = 0.01$, $\rho = 0$ and $\lambda = 0.2$. In the following this parametrization is referred to as the base case for Model 2.

Figure 2 illustrates the value of the post-smolt facility in Model 2 under two scenarios for innovation arrival.



(a) The innovation has not arrived (δ=0).



(b) The innovation has arrived (δ=1).

Figure 2: The value of the firm under different scenarios for the innovation arrival.

Here $F_{\delta,W}(R)$ denotes the value of the firm in the continuation region, i.e. the option value, whereas $F_{\delta,S}(R)$ is the value of the firm in the stopping region, i.e. the intrinsic value. Figure 2a represents the value in the case when the innovation has arrived, i.e. $\delta = 0$, whereas Figure 2b represents the value when the innovation has not arrive, i.e. $\delta = 1$. Both option value and the intrinsic value are larger in the scenario when the innovation has arrived, as the total annual profit is boosted by a factor γ. The optimal investment threshold R_0^* is larger than R_1^*, as the salmon farming company requires a larger total annual profit to be willing to invest if the innovation has not occurred. $R_{1,NPV=0}$ = MNOK 4.09 and $R_{0,NPV=0}$ = MNOK 4.2 represent the traditional NPV thresholds, i.e. the level of R such that the NPV equals zero. At the initial total annual profit $R_{(t=0)}$ = MNOK 6.125, the NPV rule suggests an immediate investment in both models.

Similarly to Model 1, this result is highly sensitive with respect to the choice of the initial profit level. For example, the situation when the expected production volume would be 300 metric tons instead of 500 initially is illustrated by the values $\hat{R}_0$ and $\hat{R}_1$ in Figure 2. The NPV rule would suggest that the investment is unprofitable in both cases, whereas the real options analysis uncovers additional value. The difference between the net present value and the real options value for the base case of $R_{(t=0)}$ = MNOK 6.125 is MNOK 4.6 or approximately 20 percent of the net present value when $\delta = 0$. For $\delta = 1$ the corresponding numbers are MNOK 3.5 and 14 percent. In both cases the excess value corresponds to the value of flexibility of the salmon farming company, that the traditional NPV approach does not account for. As in the case of Model 1, this value reaches its maximum, at the point where the NPV equals zero.

The results of the sensitivity analysis for the scenario when no innovation has arrived are presented in Table 3.

Parameter	**Symbol**	$F_{0,W}(R)$	R_0^*, R_1^*
Investment cost	K	↓	↑
Innovation arrival rate	λ	↑	↓
Profit improvement factor	γ	↑	↓
Profit volatility	σ_π	↑	↑
Profit drift	α_π	↑	↓
Quantity volatility	σ_Q	↑	↑
Quantity drift	α_Q	↑	↓
Correlation	ρ	↑	↑
Discount rate	r	↓	↑

Table 3: Effect of increase in input parameters on the value of the investment opportunity $F_{0,W}(R)$ and on the investment thresholds R_0^* and R_1^* in Model 2.

As can be seen, the investment cost, discount rate, volatility and drift parameters have the same qualitative effects on the investment threshold and the value function as in Model 1. Therefore, the following analysis focuses on the effects of the innovation arrival rate, profit improvement factor and the correlation coefficient.

As is evident from Table 3, the option value is increasing in the arrival rate, λ. A larger λ decreases the expected time until the arrival of the innovation. As the salmon farming company gets the benefits of the innovation at no cost, regardless of investment timing, the only change incurred by an increasing λ, is the proportion of time operated with and without the increased profits. Therefore, a larger λ

increases the attractiveness of the investment opportunity. Thus, the salmon farming company has an incentive to hasten the investment, and, therefore, R_0^* decreases.

Intuitively, the larger the boosts in profit is, the larger the value of the investment opportunity is. Therefore, a larger γ yields a larger expected value of the project, so that the salmon farming company is willing to undertake investment at a lower level of total annual profit. In addition, an increase in γ leads to a decline in both investment thresholds. Numerical experiments show, that the decrease is steeper for R_1^* than for R_0^*, as a salmon farming company that invests at R_1^* enjoys the benefit of the innovation for the whole lifetime of the project, whereas an investment made at R_0^* implies that the benefit from the innovation is received further in the future.

Note that in the base case it is assumed correlation between unit profit π, and annual quantity produced Q, ρ, to be equal to zero. The violation of this assumption may, however, affect the investment problem. A positive ρ results in a larger option value and larger investment thresholds, whereas a negative ρ leads to a decline in both option value and investment thresholds. Intuitively, positive correlation increases the uncertainty in the model, as a change in unit profits is more likely to be amplified by a change in quantity. In the case of negative correlation, the impact of a change in unit profits on R is likely to be dampened by an opposite change in quantity. If in the correlation of the two underlying stochastic processes increases, then the investment threshold both with and without the presence of an innovation also increases. This is because an increase in ρ increases the uncertainty in the model.

6 Conclusion

This study has offered an economic perspective on the investment in post-smolt production, one of the most promising developments within salmon farming. The objective was to examine the effects of technology and profit uncertainty on project value and optimal investment strategy in a post-smolt facility, and investigate whether real options analysis can reveal additional value compared to traditional capital budgeting methods.

The study finds that by relying on traditional capital budgeting methods, the salmon farming companies may value the investment opportunities incorrectly. Given the current characteristics of post-smolt production, traditional capital budgeting methods underestimate its potential, possibly preventing the industry from taking the next step towards meeting the growing global demand. Evaluating the specific investment case using real options approach, uncovers significant excess value compared to a traditional discounted cash flow analysis. More specifically, the value of flexibility to delay the investment decision of the salmon farming company is almost 30 percent of the initial investment cost. The traditional NPV investment rule does not account for this flexibility, and, therefore, undervalues the investment opportunity. Hence, this may lead the salmon farming companies into rejecting the sensible business opportunities by following a simple NPV criterion.

Moreover, for the initial profit level $R_{(t=0)}$ = MNOK 6.125, the intrinsic values in both Model 1 and 2 are positive, meaning that a traditional NPV analysis would suggest immediate investment. However, the results of the real options analysis suggest waiting for a more beneficial investment timing. In addition, if the initial values are incorrectly specified, the NPV of the undertaking a project today may become negative. For example, if in Model 1 investment costs turn out to be at least 22.5% larger (e.g. due to the necessity to purchase or lease the land), or, alternatively, in Model 2 the quantity of the post-smolt produced in the first year is at most 300 tons, the NPV analysis would suggest to forgo the profitable investment opportunity. The real options approach, in turn, recognizes the additional value of the investment option embedded in the project, and shows that the correct investment rule is to wait until the optimal threshold is reached, and then install the facility. The expected first passage time of the investment thresholds to be 11 and 5 years for Model 1 and Model 2, respectively. This indicates that even if the NPV analysis justifies investment in the post-smolt production, it fails to time this decision optimally. Therefore, the real options approach can significantly improve the decision making process of salmon farming companies under uncertainty.

In addition, our study discovers that the investment strategy is substantially influenced by the way the benefits of the technological uncertainty affect the firm. This is particularly relevant for the industries with a high level of information sharing, like aquaculture. In particular, salmon farmers tend to share their knowledge about new sea lice fighting technologies, as an increase in the sea lice levels at one farm negatively affects other farmers. Hence, in this case the benefits of the technological innovation, such as best practices in operating a post-smolt facility, can be gained even after the investment is undertaken. Our study shows that in this case the firm has more incentive to delay an investment, in comparison to the situation when the investment timing influences how advantageous the innovation turns out to be.

Therefore, the insights from this paper can improve decision-making under uncertainty and support post-smolt production in the debate of its economic viability. It is important to emphasize, however, that the application value of our models is in providing intuition on how uncertainty in technology and profits affects the investment problem. The models are based on several assumptions that limit the applicability of the absolute values presented.

Lastly, it is important to point out the possibilities for future research. First, profit development is assumed to follow a geometric Brownian motion. As salmon has many of the characteristics of a commodity, the post-smolt price can be modeled as a mean-reverting process. Alternatively, more complex price developments such as mean reversion with jumps could be implemented, to also allow for the post-smolt price to jump as a result of salmon farming companies having encountered mass mortality and being, therefore, willing to pay a high price for larger smolt to recover production. Second, as a post-smolt case study on a larger company would include more options than just the option to defer investment, our models could be extended by including embedded options such as stepwise investment, and expansion or abandonment options. Third, there is uncertainty tied to the future policies set for post-smolt production. Currently, salmon produced in closed production facilities is not included in the MTB, which represents a great advantage for post-smolt production. A possible alteration of the current policy poses a risk for salmon farming companies, as they might be forced to include the post-smolt in their MTB. Thus, including policy uncertainty represents another possible extension of the models presented. Furthermore, it could be interesting to view the investment problem from a game theoretic perspective of a large company. Given the current lack of commercial suppliers in the post-smolt market, first movers can achieve premium prices. At the same time the first mover would risk losing terrain to second-movers who have awaited superior technology.

Appendix A

The salmon farming company chooses the investment timing that maximizes the expected net value of the project. Therefore, its optimal stopping problem looks as follows

$$F(R_\tau, K_\tau) = \sup_\tau \mathbb{E}\left[\int_\tau^\infty \mathrm{e}^{-rt} R_t dt - \mathrm{e}^{-r\tau} K_\tau\right], \tag{4}$$

where τ represents the investment timing and r is the discount rate.

The solution space of this problem can be divided into two regions: the continuation region, where it is optimal to wait, and the stopping region, where it is optimal to invest. The optimal stopping region can be entered either by diffusion of R or by a sudden jump of K.

Let us now reformulate the problem in in terms of the ratio of total annual profits to the investment cost, $\frac{R}{K}$, that can be interpreted as a benefit to cost ratio. Both R and K are subject to stochastic development. When their ratio reaches a specified level, investment is optimal for the salmon farming company to undertake an investment. We introduce a new variable, $p = \frac{R}{K}$, in order to to simplify notation. The option value can now be written as

$$F(R, K) = Kf(p). \tag{5}$$

Hence, the problem becomes one dimensional, considerably simplifying the solution procedure.

The new variable p follows

$$dp = p\mu dt + p\sigma dz + pdq_2, \tag{6}$$

where dq_2 is given by

$$dq_2 = \begin{cases} 0, & \text{with probability } 1 - \lambda dt, \\ \frac{1}{\phi} - 1, & \text{with probability } \lambda dt. \end{cases} \tag{7}$$

The solution to the optimal stopping problem in (1) can then be expressed in terms of the optimal threshold, p^*, i.e. the ratio of total annual profits R to the investment cost K signaling an economically justifiable investment, and the corresponding value function.

The value of the salmon farmer in the stopping region is equal to

$$f_S(p) = \frac{p}{r - \alpha_R} - 1, \tag{8}$$

and the value of the option to invest, $f_W(p)$ satisfies the following equation

$$\frac{1}{2}\sigma_R^2 p^2 f_W''(p) + \alpha_R p f_W'(p) - (r + \lambda) f_W(p) + \lambda\theta f_W\left(\frac{p}{\theta}\right) = 0. \tag{9}$$

The optimal investment threshold p^* and $f_W(p)$ can be found by solving (9) in combination with the following boundary conditions[5]

$$\begin{cases} f_W(p^*) = \frac{p^*}{r-\alpha_R} - 1, \\ f_W'(p^*) = \frac{1}{r-\alpha_R}, \\ f_W(0) = 0. \end{cases} \tag{10}$$

This problem cannot be solved analytically. Therefore, in order to find a solution to (9) a numerical procedure is developed based on an implicit finite difference scheme.

Appendix B

Consider now the value of the investment opportunity, denoted by $F(\pi_t, Q_t)$. The objective of the salmon farming company is to find the optimal investment timing, τ, which translates to the following the optimal stopping problem

$$F(\pi_\tau, Q_\tau) = \sup_\tau \mathbb{E}\left[\int_\tau^{\tau+\tau_\lambda} \mathrm{e}^{-r(t-\tau)}\pi_t Q_t dt + \int_{\tau+\tau_\lambda}^{\infty} \mathrm{e}^{-r(t-(\tau+\tau_\lambda))}\pi_t Q_t(1+\gamma)dt - \mathrm{e}^{-r\tau}K_\tau\right]. \tag{11}$$

[5]These conditions represent the value matching, smooth pasting and the initial boundary condition (see, e.g., Dixit and Pindyck, 1994). The detailed derivations are presented in Appendix A.

After investment, the value of the salmon farmer consist of two components. The first term in (11) represents the profit before the arrival of innovation, whereas the second term captures an increased profit after its arrival. In order to reduce the dimensionality of the problem we perform a transformation of variables by considering the total annual profit, R_t, such that $R_t = \pi_t Q_t$. This does not change the optimal stopping problem of the firm, implying that $F(\pi, Q) = F(R)$.

In what follows we solve the problem backwards, first deriving the value of the investment opportunity given that the innovation has already arrived, which is denoted by $F_1(R)$. This situation corresponds to the case when $\tau_\lambda = 0$ in (11). Then we look at a more general problem, when the innovation has not arrived, i.e. $\tau_\lambda > 0$ in (11). The value of the investment opportunity when a technological innovation will arrive in the next period of length dt (with probability λdt) is denoted by $F_0(R)$. The total value of the salmon farming company is then equal to

$$F = F_0(R)(1-\delta) + F_1(R)\delta, \tag{12}$$

where δ is a binary variable that equal to 1 if the innovation has arrived, and 0 otherwise.

Let R_0^* and R_1^* denote the optimal investment thresholds that correspond to the cases before and after the arrival of the innovation, respectively. In other words, they represent the minimal levels of annual profits such that an investment is economically justifiable. Both thresholds con be hit either by achieving a high unit profit π, high quantity Q, or both. Then the value of the salmon farming company after the arrival of innovation is given by

$$F_1(R) = \begin{cases} \left(\dfrac{R}{R_1^*}\right)^{\beta_1} \dfrac{R_1^*(1+\gamma)}{\beta_1(r-\mu_{\pi Q})}, & \text{if } R < R_1^*, \\ \dfrac{R_1(1+\gamma)}{r-\mu_{\pi Q}} - K, & \text{if } R \geq R_1^*, \end{cases} \tag{13}$$

where

$$\mu_{\pi Q} = \alpha_\pi + \alpha_Q + \rho\sigma_\pi\sigma_Q. \tag{14}$$

The optimal investment threshold, R_1^* is equal to

$$R_1^* = \frac{\beta_1(r-\mu_{\pi Q})}{(\beta_1-1)(1+\gamma)}K. \tag{15}$$

Now, we derive the value function and the optimal investment threshold in the scenario when the innovation has not arrived, i.e. where $\delta = 0$. As long as the innovation is not introduced, the salmon farming company will hold the option to invest. However, note that the company will get the benefit of the innovation as soon as it arrives, regardless of investment timing. The value of the salmon farming company before the innovation has arrived is given by

$$F_0(R) = \begin{cases} \big(C_1 R^{\theta_1} + A_1 R^{\beta_1}\big)\big(1-\delta\big) + A_1 R^{\beta_1}\delta, & R < R_1^*, \\ \left(\frac{\lambda R(1+\gamma)}{(r-\mu_{\pi Q})(r-\mu_{\pi Q}+\lambda)} - \frac{\lambda K}{r+\lambda} + D_1 R^{\theta_1} + D_2 R^{\theta_2}\right)\big(1-\delta\big) + \left(\frac{R(1+\gamma)}{r-\mu_{\pi Q}} - K\right)\delta, & R_1^* \leq R < R_0^*, \\ \frac{R\lambda\gamma}{(r-\mu_{\pi Q})(r-\mu_{\pi Q}+\lambda)} + \frac{R}{r-\mu_{\pi Q}} - K, & R \geq R_0^*, \end{cases} \tag{16}$$

where $\mu_{\pi Q}$ and R_1^* are presented earlier, whereas A_1, C_1, D_1, D_2 and the optimal investment threshold when the innovation has not arrived, R_0^*, are obtained via value matching and smooth pasting conditions between the three regions of (16).

Numerical experiments show that the threshold R_1^* is lower than R_0^*. This is due to an increase in project value caused by innovation. Hence, the salmon farming company is expected to have weaker incentives to postpone an investment after the innovation has arrived.

In the equation (16), when $R < R_1^*$ and $\delta = 0$, the value of the investment opportunity equals the value of the option after the arrival of innovation, $A_1 R^{\beta_1}$, adjusted by the term $C_1 R^{\theta_1}$. The constant $C_1 < 0$ accounts for the fact that an innovation has not yet arrived. As λ increases, $C_1 R^{\theta_1}$ converges towards zero, as the salmon farming company is closer to possessing the option to invest with an innovation. If $\delta = 1$, the option value becomes $F_1 = A_1 R^{\beta_1}$.

When $R_1^* \leq R < R_0^*$ and $\delta = 0$, the investment will take place immediately should the innovation arrive. Therefore, the terms $\frac{\lambda R(1+\gamma)}{(r-\mu_{\pi Q})(r-\mu_{\pi Q}+\lambda)} - \frac{\lambda K}{r+\lambda}$ in (16) represent the expected net value of investment until the arrival of the innovation. The term $D_1 R^{\theta_1}$ represents the value of the opportunity to invest when the threshold R_0^* is hit from below. The term $D_2 R^{\theta_2}$ is the value of the investment opportunity in the region $R < R_1^*$, should the threshold R_1^* be approached from above. If $\delta = 1$ the value is equal to $A_1 R^{\beta_1}$, and the option is exercised immediately in exchange for the termination value $\frac{R(1+\gamma)}{r-\mu_{\pi Q}} - K$.

When $R \geq R_0^*$ the option is exercised regardless of whether an innovation has arrived or not. The termination value will be the sum of the terms in the respective domain presented in (16). The first term represents the present value of the expected total annual profits without an innovation from the time of the investment until the innovation arrives. The second is the present value of the expected total annual profits in perpetuity after the innovation arrival.

Acknowledgments

The authors would like to thank Henning Urke, Torstein Kristensen, Espen R. Jakobsen, Bjørn Hembre, Anders Jon Fjellheim, Finn Christian Skjennum, Ole Gabriel Kverneland, Kolbjørn Giskeødegård, Alex Vassbotten, participants of "Smolt production in the future" organized by Nofima in Sunndalsøra, Norway (October 2014) for their helpful insights and valuable feedback.

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