Econometric Analysis of Innovation, Productivity Growth and Efficiency:

Applications for the Norwegian Salmon Farming Industry

by

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Thesis submitted in fulfillment of
the requirements for degree of
PHILOSOPHIAE DOCTOR
(PhD)

University of
Stavanger

Faculty of Science and Technology

2016

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NORWAY
www.uis.no

ISBN: 978-82-7644-637-1
ISSN: 1890-1387

In loving memory of
our wonderful daughter

Hanne

Acknowledgements

This thesis is submitted in fulfilment of the requirements for the degree of *Philosophiae Doctor* (PhD) at the University of Stavanger, Faculty of Science and Technology, Norway. The research has been carried out at the University of Stavanger from April 2012 to September 2015. I acknowledge the University of Stavanger and the Norwegian Research Council for their financial support which made my project possible.

Writing this Ph.D. thesis has been challenging in several areas – professionally and personally. There are a number of people that have provided essential help and support during the process.

Primarily, I want to thank my three supervisors at the University of Stavanger, Professor Kristin H. Roll, Professor Frank Asche and Professor Ragnar Tveterås. I am very grateful to Kristin H. Roll which made this project possible and for giving me the great opportunity to undertake this PhD. Thank you for always being so helpful and inspiring. Your advices and feedback has been highly valuable to finish this thesis. Furthermore, I am deeply thankful to Frank Asche. You have contributed as an experienced academic adviser and knowledgeable discussion partner, but also as a promoter, facilitator and nice travelling company. Your encouragement and enthusiasm has been priceless. Next, my sincere thanks goes to Ragnar Tveterås. You are the one who gave me the courage and motivation to start this PhD. You have generously shared your academic skills with me, always in a positive, helpful, humorous and patient way. As a team, you have all been important contributors and motivators throughout the work with this thesis. Thank you for many nice coffee breaks with spirited discussions in the coffee bar.

In addition, I would like to thank Atle Øglend, Petter Osmundsen, Eric Brun and Roy Endrè Dahl, all colleagues in the INDØK group at the University of Stavanger. You have contributed to make IØRP to a good place to work. Thank you also to Arne Sørvig and Dengjun Zhang, co-authors on one paper. Furthermore, I am deeply grateful to my fellow PhD students at the departments IØRP, HHUiS and IMKS, which have provided memorable and enjoyable years. Some of you proved to be truly caring friends, giving me genuine support and generous inspiration through this PhD-journey. Thank you for sharing both ups and downs, and for valuable moments also outside the university.

I am blessed with a wonderful family. Thank you all for always being there, reminding me what really matters in life. A special thank you goes to my parents, Johannes and Jorunn Ness. Thank you both for your endless support in my academic ambitions. Daniel, Helene and Kristian, you are the most important projects in my life, and without a doubt the best results I have ever obtained. Nina, thank you for all the positive energy and happiness you bring into our family. Last, but certainly not least, I would like to thank my husband Ole Harry - my best friend through 27 years - for giving me practical and emotional support in everything I do.

Stavanger, 28th October 2015

Hilde Ness Sandvold

Summary

Although salmon farming in Norway has a relatively short history, it has developed into an important export industry for the national economy. The industry has experienced large growth in production volume; production has increased from a few thousand tons in 1980 to over 1.3 million tons in 2014. An important driver for this development has been extensive technological improvements and strong productivity growth leading to reduced production costs and improved competitiveness. A key feature for cost reduction has been better and cheaper inputs. After feed, smolt is the most important input factor in salmon farming. Smolt production has experienced rapid technological progress since the industry first stated in the 1980`s. Most of the cost savings due to productivity increase in juvenile production has been passed on to the grow-out farms in the form of lower smolt prices. This has made Norwegian salmon more competitive relative to other food producers. Hence, salmon farming is an example of an industry where technological improvements have led to productivity growth and increased competitiveness. Norwegian salmon aquaculture provides a highly relevant case in the study of innovation and economic growth.

The purpose of this thesis is to highlight the relevance of innovations in salmon production by measuring their economic effects. This is addressed by focusing on economic drivers in the industry using econometric productivity and efficiency analysis. I have used several measures to investigate and compare the performance among firms and regions over time. Among these are productivity growth, technological change, efficiency and economies of scale. The econometric analyzes uses translog production and cost functions to investigate the production technology.

My thesis indicate that the substantial productivity growth in smolt production has contributed significantly to improved competitiveness of the salmon industry. However, the results shows that productivity growth in juvenile production has slowed down, and actually become negative some years. Furthermore, the econometric analysis indicate that not all firms in the industry are operating on the technically efficient frontier. In this respect, the geographic region for smolt production matters, since some regions tend to have higher production costs than others. In addition, the analysis finds econometric support for the existence of a learning-by-doing effect in juvenile production, suggesting that older firms perform slightly better than new ones with respect to technical efficiency. Finally, an analysis of salmon farming globally shows that the degree of concentration has

increased in all the five leading producing countries. The large firms have become bigger over time.

This thesis falls in line with a large collection of economic research on the Norwegian salmon industry. The literature on productivity growth in the grow-out phase of salmon has got substantial attention. However, so far there has been paid less attention to productivity growth among the suppliers. Since juvenile freshwater production is crucial for further sustainable growth, it is my hope that the insights and results from this thesis will be of interest. Although the results apply specifically to salmon aquaculture, most aquaculture producers are exposed to similar types of regional differences and biological shocks. Therefore, the results of the analysis should be relevant to other aquaculture species as well.

Contents

PART I

1 INTRODUCTION

The economic development and social welfare in Norway is largely based upon exploitation of natural resources as oil and gas, fisheries and aquaculture, minerals, forestry and hydroelectric power. Some of these industries, like oil and gas and aquaculture farming, has developed unique skills in production and marketing in the global perspective. This has contributed to make Norway to a highly skilled knowledge based economy (Reve & Sasson, 2012). As such, major driving forces for the economic growth in Norway has been both the natural resource itself and the knowledge developed by the industries through the years.

However, several of the resource-based industries export a large share of their products to foreign markets. In these markets, they face substantial competition from low-cost producers. For Norway, a general decrease in the costs through substantial reduction in the salaries is not a likely solution to stay competitive at the international market in the future. Norway will probably remain a high cost country. To make up for this, both knowledge and expertise, renewal and the ability to adapt to rapidly changes are important factors to enhance the competitiveness (OECD, 2015; Reve & Sasson, 2012). Hence, the capability to innovate will most likely be highly required skills for competitiveness in the years to come.

Norwegian salmon farming is an example of an industry where extensive innovations have led to productivity growth and increased competitiveness. Over the last decades, the industry has increased its knowledge skills and thereby developed globally leading expertise (Asche & Tveterås, 2011). In the analysis by Reve and Sasson (2012), the marine industry in Norway is found to have the potential to become a global knowledge-hub[1].

The objective of this dissertation is to highlight the relevance of innovations in salmon farming by measuring their economic effects. Smolt is, after feed, the most important input factor in salmon farming. Consequently, juvenile freshwater production is crucial for further sustainable growth in salmon production. Hence, a particular focus will be given to the land based hatchery sector[2]. The issue in the thesis is addressed by focusing on economic drivers in the industry by using econometric productivity and efficiency analyzes.

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[1] Global knowledge hubs or superclusters are characterized by a high concentration of innovative industrial actors interacting closely with advanced research institutions, venture capital and competent ownership (Reve & Sasson, 2012).

[2] The farmed salmon is raised in floating cages in the sea, but this is after an initial period in land-based freshwater farms, often called hatcheries. The period in freshwater is 8 to 16 months. A normal life cycle for a farmed salmon is between 2 and 3 years, depending on the individual growth. The fish is called a smolt when it is physical ready for transfer to saltwater. This occur at a weight of around 70-100 gram.

1.1 *Structure of the thesis*

The thesis consist of four papers. All of them deal with economic growth in the salmon farming industry. Furthermore, the thesis is presented in two parts. Part I is the introduction and contains of four chapters. The first chapter sets the context for the research by offering a brief introduction to the concept of innovation. The second chapter gives a presentation of the theoretical and methodical foundation of the papers. The third chapter is dedicated to the salmon industry. The fourth and final chapter offer a short summary of the papers. Part II presents the four papers in their entirety.

The remaining of the Introduction chapter is as follows: First, I will briefly discuss some relevant issues in the concept of innovation. Second, I will present my approach for measuring the effects of innovation and economic growth.

1.2 *Innovation*

Even if the theoretical concept of innovation has got substantial attention the recent years, it is not a new phenomenon. Eighty years ago, Schumpeter used the phrase *Neue Kombinationen* (1934). He described innovation as new combinations of production factors. Recent literature describes innovations as the ability to combine existing resources in new ways (Fagerberg et al., 2005). Furthermore, the new combinations will often be carried out through the actions of a particular type of economic agents called *entrepreneurs* (Schumpeter, 1935, 1994).

1.2.1 *Innovation as a catalyst to economic growth*

Schumpeter also argued that innovation is a necessary driver to renewal that will increase the economic performance in an organization (1934). Improvements and innovations will help the firms to develop new products or processes, and very often they become more productive. Economic growth in an industry or a society occur when many firms becomes better (Solow, 1956). This will advance the technological frontier.

Innovation is a key driver of economic progress and an important determinant of economic prosperity. Innovative skills is a crucial factor in determining competitiveness and national progress (OECD, 2007, 2015). As such, innovation can be an explanatory factor behind differences in performance between industries, firms, regions and countries. Innovative countries and regions tend to have higher income and better performance than the less innovative ones (Furman, Porter, & Stern, 2002; Rosenbusch, Brinckmann, & Bausch, 2011)[3]. Hence, policy makers and

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[3] However, while a positive correlation between product innovation and firm's performance has been established for European firms, evidence for developing countries has been mixed (Rosenbusch, Brinckmann, & Bausch, 2011).

business leaders alike are concerned with ways in which to foster innovation (OECD, 2015).

1.2.2 *Innovation and the role of the authorities*

Innovation will easier result in economic growth if market structures and the regulatory environment enable the more productive activities to take place and expand (Blind, 2012). The authority's policy can affect firm's ability to perform innovation, directly or indirectly (OECD, 2007, 2015). Directly, by continually reforming and updating the regulatory and institutional framework within the innovative activity takes place. Hence, establishing appropriate regulations can be a key component of ensuring adequate competition and innovation. The government can also support innovation, indirectly, by public investment in science and research. An appropriate mix of indirect and direct instruments such as tax credits, direct support and well-designed public-private partnerships can be a support for innovative activities.

1.2.3 *Innovation in high cost societies*

In the parliamentary report called *The world's leading seafood nation,* the Norwegian government launches their proposals for long-term policy for the seafood industry (Stortingsmelding nr 22 (2012-2013), 2013). Further development and growth for the salmon industry will create some opportunities and some challenges. Besides the environmental issues[4], one of the largest challenges for further growth will be the fact that Norway is a high-cost country. The salmon products are distributed to international markets where the industry faces the same customer requirements from retailers and restaurant chains like other international suppliers of food do. In these international markets, salmon is compared with other suppliers, and compete on factors as product quality, delivery reliability and cost efficiency. Hence, as an international supplier of food, the industry compete with food products from countries with lower production costs. As such, the producers are exposed to both price pressures and continuous requirements to adapt to changes in the market. This require the ability to innovate rapidly. For high cost countries like Norway, it is particularly important to acquire and use the unique knowledge effective in order to maintain the innovations process and the economic development (Reve & Sasson, 2012).

1.3 *Measurement of innovation*

The economic value an industry or a society achieves from innovation can be measured. In this thesis, I use econometric

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[4] In the wake of the rapid expansion of salmon farming, a number of environmental concerns, like effluent discharges, escaped farmed salmon, diseases, the use of medicines and chemicals and the taxation of wild fish stocks, has emerged (S. Tveterås, 2002).

methods to measure economic growth and estimate the effects of innovation.

The traditional neoclassical approach is largely based on the work of classical economists and extended by Solow (1956, 1957). He indicated that the unexplained share of long-run economic growth in classical economic models tended to be very high. Therefore, he drew attention to the technological change as a measurement of economic growth not explained by increased use of the input factors. Innovation in this context is treated as the technical change in the production technology. The framework for evaluating innovation and economic growth is based on a quantitative toolbox with mathematical models and the use of statistical theory to interpret the results. Economic growth theory make use of production, cost or profit models which provide a theoretical framework for understanding production growth by aggregated output (y) as the dependent variable and input factors as labor (L) and capital (C) (Greene, 2012). The innovations will move the product function upwards, as firms produce more because of the technical progress they experience. Likewise, the innovations will move the cost function downwards, as the costs will be reduced in the long run. As such, technical progress from one year to another is the economic measure of the innovation that has taken place, and identified by technical change in econometric analyzes.

2 THEORY AND METHOD

In the theory of production economics, productivity and efficiency are frequently used to measure economic performance. The purpose of this chapter is to introduce the theory of productivity and efficiency, as well as describe different methods which can be used to measure these economic variables.

2.1 *Productivity and efficiency*

Although closely related, productivity and efficiency are two fundamentally different concepts (Coelli, Rao, O'Donnell, & Battese, 2005; Fried, Lovell, & Schmidt, 2008). Productivity describes the physical relationship between output and input and is defined as output per unit of input. As such, productivity is an absolute measure of how much output a firm will produce, given the amount of inputs. It is a pure physical performance measure. A high score will indicate a high productivity.

Productivity growth between two periods is measured as growth in output, which is not achieved by increased use of inputs. In econometrics, total factor productivity growth is the most frequently used concept. It is a measure that includes all input factors of production.

Furthermore, efficiency is also a measure of performance. It differs from productivity by being a relative measure, not an absolute one. Efficiency describes the relationship between the actual production and the highest production achievable. The production frontier is frequently used to represent best practice. The frontier is defined as the maximum possible output a firm can produce given a set of inputs and its technology. Efficiency measurement by production frontiers involves a comparison of the firms actual performance with optimal performance which is located at the frontier. Producers operating on their production frontier are defined as technically efficient, and producers operating beneath their production frontier are defined as technically inefficient. These producers can become more productive by increasing their efficiency.

Competitive producers need to be both productive and efficient in the production process. Failure to achieve this will directly lead to higher costs and weaker economic performance.

2.1.1 *Sources of productivity growth*

Both internal and external factors can affect the performance of firms or industries (Coelli, Rao, O'Donnell, & Battese, 2005). If these variables are added to the model, it will give the possibility to distinguish between shifts in the frontier caused by internal or external influence. In production industries, external factors like government regulations, localization characteristics and ownership differences may affect the production and thereby influence the performance. Internal sources that can affect the performance for a firm or an industry can for example be technological progress, exploitation of scale or technical efficiency improvements.

Technological progress is usual seen as the consequence of an innovation and adoption of new technology. It is a measure of the improvements that has taken place. In the econometric models, technical change is specified with the use of a time trend t. A time trend represents the development of new technologies that allows the production to improve. The technological progress will drive the long-term economic growth, because after the introduction of an innovation the firm will be able to produce more from a given amount of inputs than it could before the innovation took place. Hence, investments in innovations and new technology will move the front upwards. The level of best practice changes with better technology, and this will contribute to a better performance for all the firms in an industry.

To fully be exploited, some innovations require an increase in the scale of production. As such, exploiting of scale economies comes as an additional effect to the effect of innovations and technological progress. Scale efficiency is a measure of how far a firm is from operating at optimal scale. Economies of scale is the property of a cost function whereby the average cost of production falls as output expands. By contributing to lower the costs, the scale contribute to increase performance and productivity growth.

In general, one expects that the productivity growth is positive, because one normally do not lose knowledge or expertise. However, productivity growth from one period to another can decrease and even become negative (Coelli, Rao, O'Donnell, & Battese, 2005). Several reasons for negative productivity growth can occur. In the context of resource based production economics, I will mention three different reasons for negative productivity growth. First, it can be observed in firms or industries that experience biophysical shocks. Second, it can occur if firms or industries use inputs factors of poor quality, for example according to overexploitation of a natural resource. A third reason for negative productivity growth may be found in growing industries that experience too static regulatory restrictions. In fast growing industries, there is a need for the regulations to be dynamic and adaptive to the technological progress.

To maximize the profit, a firm must produce as efficiently as possible (Fried, Lovell, & Schmidt, 2008). A firm gets an efficient production (achieves technical efficiency) if it cannot produce its current level of output with fewer inputs, given a fixed set of inputs and given a certain technology. Efficiency is the degree to which a production process reflects best practice either in a technical sense (technological efficiency) or in an economic sense (allocative efficiency). Improvements in a firm’s technical efficiency will increase productivity by using a fixed amount of input more efficiently and thereby produce more outputs with the same resources. Improvements in the general efficiency for an industry includes that inefficient firms catch up with the best practice technology and comes closer to the front. Technical inefficiency is a factor not intended, but still present, for many producing firms. A production plan is technical inefficient, if a higher level of output is technically attainable for the given inputs, or that the observed output level can be produced using fewer inputs.

2.1.2 *Illustration of productivity and efficiency*

In Figure 1, a simple production process in which a single input (x) is used to produce a single output (y) is depicted. The figure is an illustration of how technological progress, exploitation of scale and technical efficiency improvements affects the performance of a firm. Following Farrell‘s (1957), the frontier can be depicted as curve F_0. The production frontier F_0 defines the set of all input-output combinations which are possible, given the technological and organizational boundaries. Firms that are located on the frontier are considered to be technical efficient, and firms located under the frontier are considered to be technical inefficient. In Figure 1, company A is not fully efficient. The firm should consider moving the production, either to point

B by decrease the use of inputs without reducing output (input oriented adaption), or to point C by increasing the level of output without increasing input (output oriented adaption). Point C represent the production where the highest productivity takes place, because it is the point where the most productive scale is obtained. The different rays $(y/x)^A$, $(y/x)^B$ and $(y/x)^C$ through the origin are used to measure the productivity for the firm. The slope of the ray will define the productivity.

Technological change involves advances in the technology that can be represented by an upward shift in the best-practice production frontier from F0 to F1 (likewise a downward shift in the cost frontier). The dashed production curve (F1) shows the maximum feasible production, in the period after the technical changes have taken place. The innovations will give more output with less input. The scale efficient point will therefore be moved to point D.

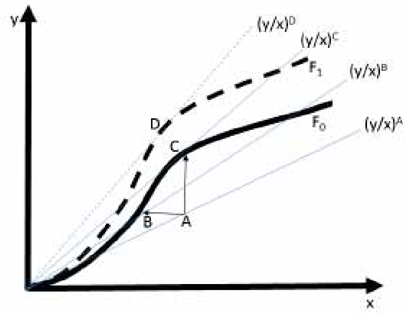

Figure 1: Productivity, technological progress, exploitation of scale and technical efficiency improvements.

2.2 *Measurement of productivity and efficiency*

Various approaches are available to measure firm's performance over time. The most commonly used methods are Econometric Production Models (EPM), Total Factor Productivity (TFP) index, Data Envelop Analysis (DEA) and Stochastic Frontier Analysis (SFA). All these models can measure economic variables like technical change, returns to scale and productivity. However, these methods differ in various ways. For example, some are parametric and some are non-parametric, and some can accommodate the effects of data noise while others cannot. Furthermore, some, but not all, can be used to measure technical efficiency and allocative efficiency. Some of them can be used for times series data while others cannot, and some require price data and others not. The main differences and similarities are summarized in Table 1.

Table 1. Summary of Properties of the Four Principal Methods (Coelli, Rao, O'Donnell, & Battese, 2005).

Attribute	**EPM**	**TFP**	**DEA**	**SFA**
Parametric Method	Yes	No	No	Yes
Accounts for noise	Yes	No	No	Yes
Can be used to measure:				
Technical inefficiency	No	No	Yes	Yes
Allocative efficiency	Yes	No	Yes	Yes
Technical Change	Yes	No	Yes	Yes
Scale Effects	Yes	No	Yes	Yes
TFP Change	Yes	Yes	Yes	Yes
Data used:				
Cross sectional	Yes	Yes	Yes	Yes
Time Series	Yes	Yes	No	No
Panel	Yes	Yes	Yes	Yes
Requires data on:				
Input quantities	Yes	Yes	Yes	Yes
Output quantities	Yes	Yes	Yes	Yes
Input prices	No	Yes	No	No
Output prices	No	Yes	No	No

2.2.1 *Econometric Production Models (EPM)*

In production econometric, the empirical estimation of production, cost, revenue and profit functions are normally used. These models represents an ideal; the maximum output attainable given a set of inputs, the minimum costs of producing that output given the prices of the inputs, or the maximum profit attainable given the inputs, outputs and prices of the inputs (Greene, 2012). The functions express a dependent variable as a function of one or more explanatory variables, also called independent variables. Mathematically, these functions will all be written in the form like $y = f(x_1, x_2 \ldots\ldots x_N)$ were y is the dependent variable and a function of x_N represent the explanatory variables. Thus, the first step in econometric estimation of the relationship is to specify the algebraic form of $f(.)$ which gives rise to different models. Examples of common functional forms are linear, Cobb-Douglas and translog. Cobb-Douglas are first-order flexible and translog are second-order flexible. However, increased flexibility comes at a cost. The second-order models have far more parameters to estimate, and this may give rise to econometric challenges. However, the translog form of the production function is frequently used, and can generally be specified as:

$$ln\ y_{it} = \sum_j \alpha_j ln\ x_j + 0.5 \sum_{jk} \alpha_{jk} ln\ x_j ln\ x_k + \alpha_t t + \alpha_{tt} t^2 + \sum_j \alpha_{jt}\ t\ ln\ x_j + v_{it}$$

where the dependent variable $ln\ y_{it}$ is the natural logarithm of output of firm i in time t (years). In the model, t is the time trend included to represent technological change (or innovations in the production technology) shifting the production frontier over time. The v_{it} are the random error term which accounts for statistical noise. It is assumed to be independent and identically distributed with zero means. The α`s are parameters to be estimated.

When studying productivity development over time, a central measure of interest is the rate of technical change. The rate of technical change (TC) is our measure of how innovations and other factors influence productivity growth, as it is not possible to observe variables that measure impact of innovations and the adoption of these directly. The rate of technical change from year t-1 to year t is specified as:

$$TC = (\alpha_t - \alpha_{t-1}) + \sum_i ((\alpha_{it} - \alpha_{it-1}) \ln w_i) + (\alpha_{yt} - \alpha_{yt-1}) \ln y$$

where the first term on the right-hand side of the equation is “pure” or neutral technical change (in the sense that it is not scale- or input-biased), the second term is input-biased technical change and the third term is scale-biased technical change. The input-biased technical change shows the effect of technical change on productivity associated with input levels, and the scale-biased technical change shows the effect of technical change on economies of scale.

TC will in many cases appear to be positive. However, in a biological production sector such as salmon farming the empirical estimate of TC will be influenced by biophysical shocks such as diseases and temperature variation, and it is therefore possible to obtain negative rates of technical change. If there is technical progress and no “noise” from biological shocks or other shocks the cost based TC measure is negative.

There are a number of different approaches to estimate the parameters of the regression model. The method of least squares (OLS) has long been the most popular to estimate the coefficients. Other frequent used approaches to estimate the parameters are the maximum likelihood estimator (MLE) and seemingly unrelated regressions (SURE). Using these techniques, the difference between the observations and the regression line becomes a minimum. The overall solution minimizes the sum of the squares of the errors made in the results of every single equation.

Conventional econometric models is frequently used to measure productivity and productivity growth, returns to scale, technological progress and elasticities of substitution. However, they assume that all firms are efficient in production and cannot be used for efficiency analysis.

2.2.2 *Total Factor Productivity (TFP) index*

Index numbers are statistical ratios that represent a weighted sum of the selected economic variables. The use of index numbers in the measurement of changes in total factor productivity lead to the popular Total Factor Productivity (TFP) index. Conceptually, quantity indexes numbers may be measuring changes in quantities of outputs produced or inputs used by a firm or an industry over time or across firms.

If all inputs are accounted for in the index, then total factor productivity (TFP) can be taken as a measure of an economy's long-term technological change. Total factor productivity index is defined as the ratio of an aggregate output quantity index to an aggregate input quantity index. Productivity growth is present when an index of output changes at a higher rate than the corresponding index of inputs.

Two common methods to measure total factor productivity are the Hicks-Moorsteen productivity index and the Malmquist productivity index. The Hicks-Moorsteen productivity index measures growth in output, net of growth inputs. The technique was developed by Diewert (1992), and draws upon earlier works of Hicks (1961) and Moorsteen (1961). This technique is relatively easy to use, but it does not allow the productivity to be divided into technological change, technical efficiency or scale efficiency change. The Malmquist total factor productivity index was introduced by Caves, Christensen and Diewert (1982) building on Malmquist distance functions. It is, relative to reference technology, constructed using input or output distance functions to measure the radial distance of the observed output and input vector between two periods. The advantage with this approach is that the change in productivity can be divided into technological change, technical efficiency change or changes in scale efficiency. This technique has become the standard approach in productivity measurement over time, especially when nonparametric specifications are applied to micro data.

The advantage with the index techniques are that they are non-parametric and therefore does not require a specific functional form representing the underlying production process. However, there are two disadvantages with the approaches. First, the methods assume all firms to be technical efficient and constant returns to hold. Second, the techniques are deterministic and ignore the existence of disturbances or external "shocks" that may alter the data's future pattern.

2.2.3 *Data Envelop Analysis (DEA)*

In efficiency studies, the Data Envelop Analysis (DEA) is a frequently used non-parametric method. The DEA approach make use of mathematical programming methods to construct a piecewise surface, or a frontier, that envelope the data. The production frontier represents a firm's production possibility curve and shows the maximum possible output combinations of two products or services an economy can achieve, when all resources are fully and efficiently exploited. Efficiency measures are calculated relative to the frontier. As such, production efficiency relates actual output to the maximum possible, and is defined as the ratio of the actual output to the maximum potential output.

The method was first introduced by Charnes, Cooper and Rohdes (1978) based upon the work of Farrell (1957). The DEA approach can be categorized according to the type of variable and data available. With only quantities available, technical efficiency can be estimated, whereas allocative efficiency can be measured if both prices and quantities are available. Scale efficiency can be identified by relaxing the assumption of constant returns to scale.

Like the index techniques, a major drawback of the non-parametric DEA approach is that it does not consider statistical noise. Based on this assumption, any deviation from the frontier is assumed to be a result of inefficiency. In biological production, random shocks outside the control of the firm can influence the efficiency. Consequently, the method can provide inaccurate efficiency measure. However, the DEA approach is computationally simple and can be credited for not requiring algebraic mathematical specification form for the production function. The frontier can be used without knowing whether output is a linear, quadratic, and exponential or some other function of inputs.

2.2.4 *Stochastic Frontier Analysis (SFA)*

Stochastic Frontier Analysis (SFA) is an alternative method for frontier estimation, when using parametric models. The frontiers estimated by this approach are consistent with neoclassical econometric theory and can be viewed as an extension of the productivity analysis in the traditional approach. In reality, producers are not always efficient in their production, and SFA method takes this into account.

Using the SFA approach, the stochastic frontier is first estimated econometrically, and then the efficiency is found relative to the frontier for each observation (Kumbhakar & Lovell, 2000; Kumbhakar, Wang, & Horncastle, 2015). For production efficiency, the frontier define the maximum production level. If a firm’s actual production is located under the frontier, the inefficiency is defined as the distance from the observed point and up to the frontier. For cost efficiency, the frontier define the potential minimum cost, and the actual cost lies above the minimum frontier owing to inefficiency. A stochastic frontier allows for statistical noise and addresses the sensitivity problem by including the composed error term with a two-sided symmetric term and a one-sided component. Using this method, the efficiency estimates are identified separately from the usual white noise stochastic term.

The general stochastic frontier production function for panel data can be defined as:

$$ln\ y_{it} = f\ (x_{it},\ t,\ \alpha) + v_{it} - u_{it}$$

were y_{it} denotes the production output of the i-th sample firm (i = 1,2.......n) at time t. The production function $f\ (x_{it},\ \alpha)$

represents the technology were x_{it} is a vector of input quantities used by the i- th firm at time t. The vector α is the corresponding coefficient vector of parameters to be estimated, and $v_{it} - u_{it}$ is the composite error terms. v_{it} is the normally distributed zero-mean error term. The component is symmetric, distributed independently of u, i.e. $v \leq 0$. The random variables have an $N\ (0,\sigma^2_V)$-distribution, meaning that the expected value of them are likely to be zero. v, represents the random, uncontrollable factors on each producer like weather, strikes and luck. It captures the effects of statistical random disturbance, and is the usual symmetric random "white noise" error term. The second component, u_{it} is the asymmetric, non-negative part of the error term. It represents the effect of production inefficiency, and if $u_{it} > 0$, the observed output is bounded below the production frontier. u_{it} is the truncation (at zero) of the $N\ (\mu_{it},\ \sigma^2)$-distribution, where μ_{it} is a function of observable explanation variables and unknown parameters. u, represents the individual firm deviation due to factors within a manager`s control. This are organizational factors that constrain firms from achieving the maximum output from their given sets of inputs and technology. u is intended to capture the technical inefficiency. $u \leq 0$ in a production frontier because inefficiency will decrease the production by wastage in the use of input factors. In a cost frontier context assuming a cost minimizing behavior, the stochastic frontier model can be expressed as:

$$ln\ C_{it} = f\ (y,\ w_{it},\ t\ \beta) + v_{it} + u_{it}$$

were C represent the costs of production of the firms (i) at time t. The cost function $f\ (y,\ w_{it},\ \beta)$ denotes the costs were y is the output, w is the prices of the input factors and β is the coefficients to be estimated. $v_{it} + u_{it}$ is the composed error terms, were u_{it} represents the cost inefficiency. $u \geq 0$ in a cost frontier because inefficiency will increase the costs by wastage in the use of input factors.

As shown, this method assumes a given functional form for the relationship between inputs and output. When the functional form is specified, then the unknown parameters of the function need to be estimated using econometric techniques. These requirements make SFA more computationally demanding than DEA. However, the advantages make the extra computational burden worthwhile.

3 THE NORWEGIAN SALMON FARMING INDUSTRY

The development of the Norwegian salmon farming industry is an interesting case when it comes to innovation and economic growth. During the last 30 years, productivity-enhancing innovations have been introduced in several areas (Asche & Bjørndal, 2011). This has largely laid the foundation for the substantial growth in production volume. From a relatively insignificant production of 31 thousand tones in 1985, Norwegian salmon production has increased to 1.3 million tons in 2014[5]. This makes Norway the world`s leading producer of farmed salmon (Asche & Bjørndal, 2011). Only a handful of countries produce significant quantities of salmon. The five largest producer countries are Norway, Chile, Scotland, Canada and Faroe Island. Norway has been the largest producer throughout the industry's history, and had a production share of 53 % in 2014.

3.1 *Production growth and lower production costs*

The rapid development in Norwegian salmon farming has been possible due to a strong productivity growth that has reduced production costs and improved competitiveness (Asche, 2008; Asche, Roll, & Tveteras, 2009). A number of studies have documented the rapid productivity growth and

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[5] The Norwegian Directorate of Fisheries fiskeridir.no

the decline in production cost in Norwegian grow-out farming (Andersen, Roll, & Tveterås, 2008; Asche, 1997; Asche, Guttormsen, & Nielsen, 2013; Asche, Guttormsen, & Tveterås, 1999; Asche, Roll, & Tveteras, 2009; Asche, Roll, & Tveterås, 2007; Guttormsen, 2002; Kumbhakar & Tveterås, 2003; Roll, 2013; Tveterås, 1999; Tveterås & Battese, 2006; Tveterås & Heshmati, 2002; Vassdal & Holst, 2011) . The increased productivity is a result of improved input factors and increased control over the production process (Anderson, 2002; Asche, 2008). Furthermore, there are evidence of economies of scale at the farm and firm level (Roll, 2013). In addition, demand growth (Asche, Dahl, Gordon, Trollvik, & Aandahl, 2011), changes in industry structure and productivity growth in the supply chain (Kvaløy & Tveterås, 2008; Larsen & Asche, 2011; Olson & Criddle, 2008) has also contributed to increased production.

Figure 2 illustrates the development of production volume in tons, sales prices per kilo and production cost per kilo in the Norwegian salmon farming industry from 1985 to 2013. In 1985, the current real unit production costs were 72 NOK per kilo, while in 2013 it has decreased to 23 NOK. This is equivalent with a decrease of 68%. The substantial cost reduction provides evidence that a substantial technological change has taken place, but the development also indicate that the technological progress may have been higher in earlier years. The real sales price per kilo has also experienced a clear downward trend in the period. In 1985, the sales price was around 100 NOK per kilo. In 2013, it had decreased to 41 NOK. This is equivalent with a decrease of 59%. Even though real prices have been falling, the producers have kept the profit margins positive in most of the years (except the years 1987 and 1991).

Lower production costs have been important for making the salmon industry more competitive, as a decline in sales price has been necessary to induce higher consumption of salmon. As the cost reduction has been translated into lower prices, it is also clear that the productivity gains have been passed on to the consumers. The main effects for the producers are that they become larger and hence earn a higher profit because of larger quantities produced.

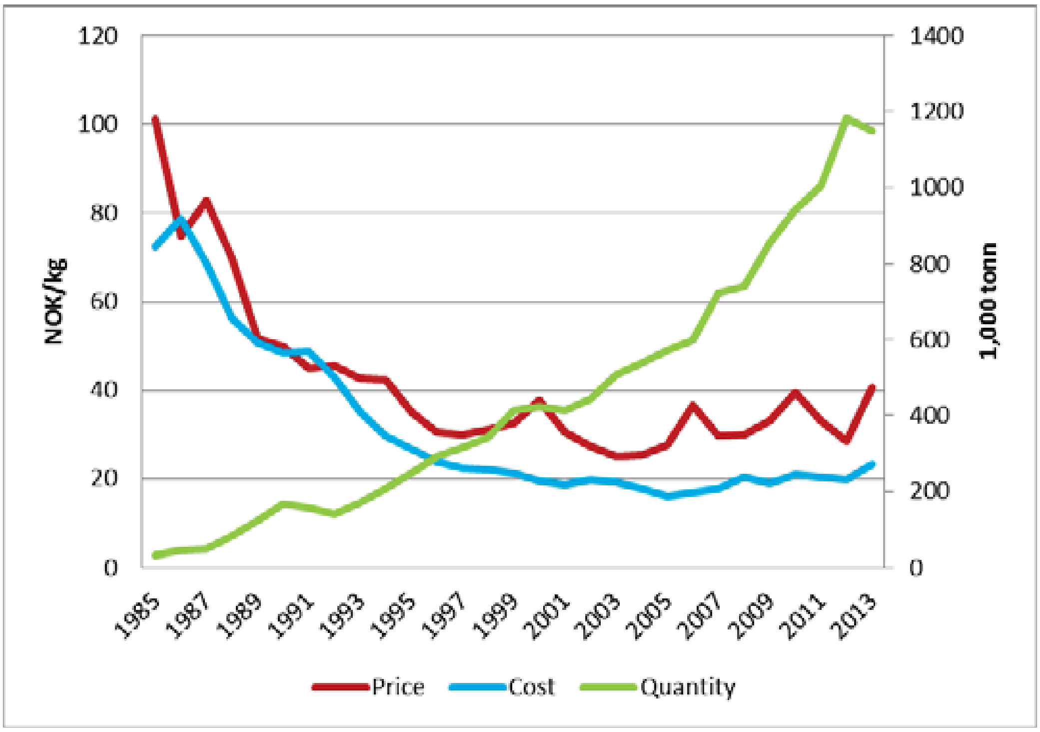

Figure 2: Real Norwegian export price and production cost 1985-2013 (2013=1) and total production of salmon.

3.2 *Innovation in salmon farming*

When the industry first started up in the 1970's, the fish farmers had a practical and commercial approach to innovations. The family owned company typically got valuable knowledge from interaction with other entrepreneurs. There were created clusters when the fish farmers met informally and shared their knowledge on best practices. Many innovations took place as copying of each other's practical solutions in the production. As such, the channels for the flow of information were short because "everybody knew everyone". Learning happened largely by on-shore experiments. However, these clusters also included the supplier industries, like the suppliers of genetics and breeding, technology and equipment's, feed, fish health and vaccination. The network of knowledgeable suppliers became very important source of innovations for the farms. The interaction between producers and suppliers created unique possibilities for improvements and technological progress. For example, innovations typically could take place when a new steel construction or a new type of feed was tested by the farm. During this cooperation and communication, unique knowledge and experience were developed. As such, the firm was engaged in innovation projects without bearing the total financial burden of the risk. In this period, the innovations were mainly intended to reduce costs (Asche & Bjørndal, 2011), and the clusters seemed to have a cost-saving effect (Tveteras & Battese, 2001; R. Tveterås, 2002).

As the industry structure was changed and the firms developed into larger units, many firms organized themselves more professionally. The firms gave more attention to academic research and scientific knowledge. The clusters were extended to include collaboration with national and international partners in both academia and research institutions. The fact that the innovation activities became a part of the strategic plan in the firm, turned out to be a valuable source of the innovations. Another valuable resource of innovations was the increased use of market signals. The products faced increased customer demands, like the demand for high quality, reliability in deliveries, food safety and expectations of traceability. Increased customer requirements changed the motivation for innovation activities, from a cost reduction activity to a necessary adoption to market changes. Thus, the firms has gradually taken more initiative to the innovations and now tend to finance more of them than earlier stages of the industry’s development.

The innovation process in salmon farming in Norway has therefore been both experienced-based and scientific-based. The suppliers have been an important source of knowledge throughout the whole period, by developing monitoring equipment, feeding systems, new and better feed and health- and veterinary services. This has led to important innovations which has given better control in the production process and a more intensive production (Anderson, 2002; Asche, 2008)

3.3 *Production of juvenile salmonids*

High productivity in all stages of the value chain increases the competitiveness of an industry. As such, it is useful to examine the development of the suppliers to improve the understanding of the factors that increase the competitiveness of Norwegian salmon farming. Productivity growth among the providers of input factors will largely reduce costs in the grow-out phase.

Tveterås and Heshmati (2002) reported that two thirds of the reduction in costs that has taken place in Norwegian salmon farming can be attributed to better and cheaper inputs. Furthermore, Asche (2008) indicated that a substantial productivity development seems to take place among input providers. In salmon production, smolt is the second most important input factor as measured by cost share (Asche & Bjørndal, 2011).

3.3.1 *Innovation in smolt farming*

Innovations have the largest impact when they occur for the most important input factors in terms of cost shares. The technological development in land-based freshwater production has been extensive from open pond-systems to the current closed or semi-closed production systems with a high degree of control. Many of the largest innovations in salmon farming have first taken place in smolt production, for example artificial light, water purification system and vaccines.

Figure 3 gives an overview of the most important innovations that has taken place in smolt production from 1970 to 2010. The vertical axis gives years in 10-year sections. The horizontal axis shows five categories in smolt farming like breeding, feed, fish health, technology/equipment and production. The first four categories describes innovations that have taken place, and connects them to the actual time period it first took place. The last category describes how the innovations have affected the production process.

In breeding and genetics there have been innovations contributed to reduction in the production time, improved feed efficiency, better survival and improved meat quality since the industry started up in the 1970`s. Two attributes that have been particularly emphasized in the breeding program, are the ability to be efficient and robust. Efficient attributes include good production and quality benefits as growth, color, fat content and body shape. Robust attributes means good health properties as resistance against specific diseases, reduced deformities and reduced early sexual maturity.

In nutrition and feed formulation, there have been major improvements. Important milestones within the fish feed development have been the transition from wet feed to the dry feed, the use of granulated pellets, autoclaving and the production of micro-pellet for the juveniles. The food has gradually become better adapted to the fish`s true nutritional needs.

Furthermore, improved fish health through vaccination has been among the most important measures to prevent spread of diseases. Vaccines for salmon were first developed in the late 1980s, which led to a huge reduction in the use of antibiotics (S. Tveterås, 2002). The juveniles are all routinely vaccinated against diseases such as furunculosis, vibriosis, coldwater vibriosis, winter wounds and IPN.

Technologically, there has been large improvements in equipment's used for smolt production with the use of artificial light as one of the most important ones. Daylight plays an important impact on the smoltification process, and for juveniles the extra photoperiod makes the fish earlier ready for saltwater. The industry started to experiment with artificial light at the end of the 1980s and it is now an integrated part of the production process in salmon farming, both before and after release to the sea. Another important technological innovation in smolt production is the use of water purification system. The Recycling Aquaculture System (RAS), which reduces the demand for water dramatically, is increasingly replacing the traditional flow-through systems. Water recycling involves the removal of particles, nitrogenous metabolites and carbon dioxide, as well as the addition of new oxygen. In addition, the system will have several positive effects as better control of the temperature and water quality.

Because of these innovations, the hatcheries can usually carry more than one generation of fish in the farm within a year. The *zero-year-old* smolt is transferred to the sea the autumn after hatching, and the *one-year-old* smolt is released the second spring after it is hatched. Earlier smoltification and increased growth due to technology improvements and innovations gives a higher degree of flexibility and utilization of the capacity for both the land-based production and the grow-out farms.

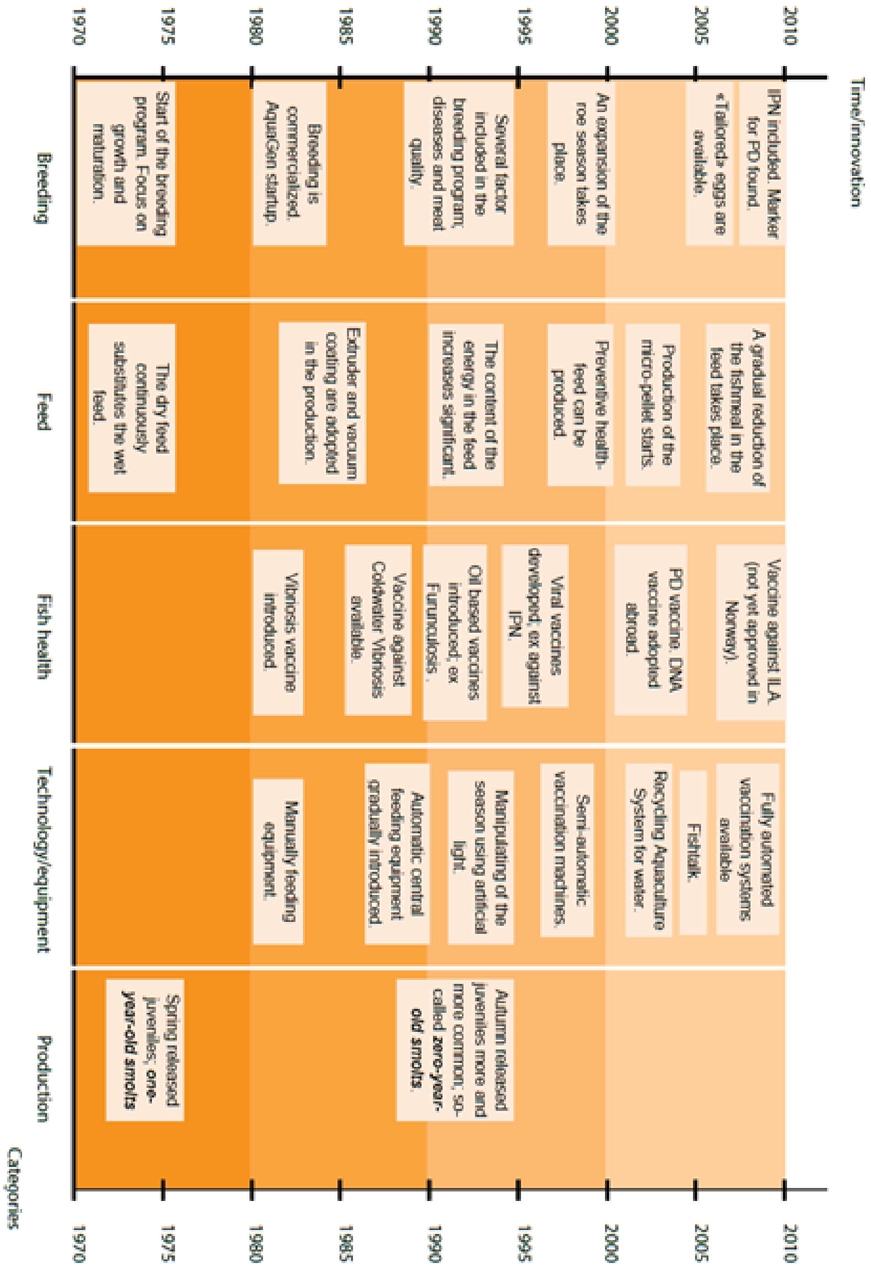

Figure 3: Overview of the most important innovations in juvenile production from 1970-2010.

3.3.2 *Effects of the innovations*

All the technological innovations and the increased knowledge about how to produce a healthy and robust smolt have influenced the production process a lot. First, the introduction of the water purification system has contributed towards a more environmental sustainable production. New hatcheries today has close to zero escapes, a low water consumption and an effective cleaning of the outlet-water. A better control in the production process has reduced the risk when it comes to accidents, escapees and diseases. Second, (as illustrated in the last category in Figure 3) earlier smoltification and several releases allows the hatcheries to produce more than one generation of fish within a year. The zero-year-old smolt is hatched in January and released to the sea in August/September the same year. The one-year-old smolt is hatched in January and released to the sea in April/May the year after.

Figure 4 offer an overview of the different generations and production cycles in smolt production during the period from 1980 to 2010. The horizontal axis gives years in 5-year sections. The vertical axis shows the four different generations of smolt that are, or have been, produced in juvenile farming.

The figure provides evidence that the innovations has resulted in major changes in the production cycles. As illustrated, the production of *two-year-old* smolts stopped in the end of the 1980`s because better and more effective production methods were developed allowing earlier release. *One-year-old* and *one-and-a-half-year-old* smolt have been produced during the whole period, even though *one-and-a-half-year-old* smolts have been less used the last years. However, the largest change is the increasing use of the *zero-year-old* smolts since the 1990`and onwards. The possibility to release the smolt at the age of 8-9 months, rather than after two years, gives evidence that substantial technological improvements have taken place.

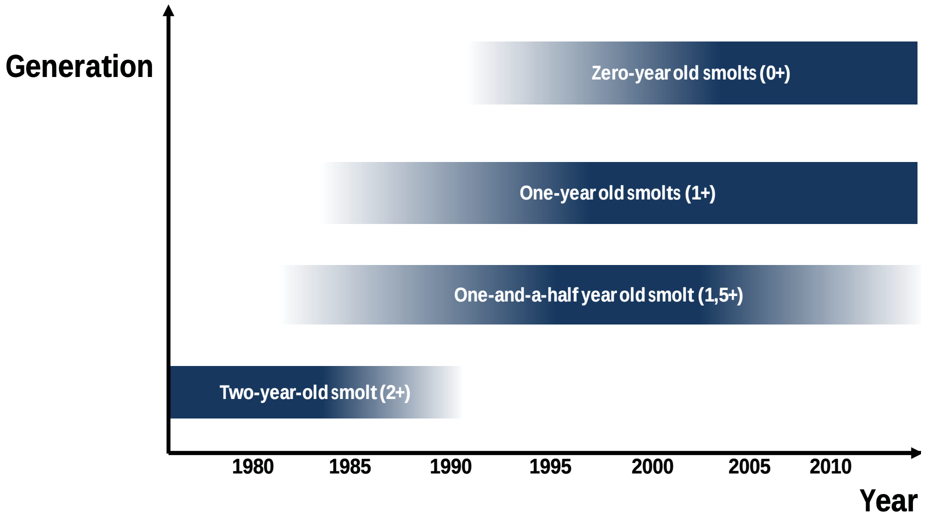

Figure 4: Comparison of the dominating cohorts in smolt production at different stages and periods in which these has taken place.

The restructuring of the production process to carry several generations in the hatchery, can be illustrated as in Figure 5. Figure 5 offer an comparison of two types of production lines. The upper one is a production line using 16-17 months, as was the standard in the 80`s and early 90`s. The lower one is a production line using 9-10 months, as has become more and more a standard. As shown, the use of artificial light shorten the growth period of 5-6 months.

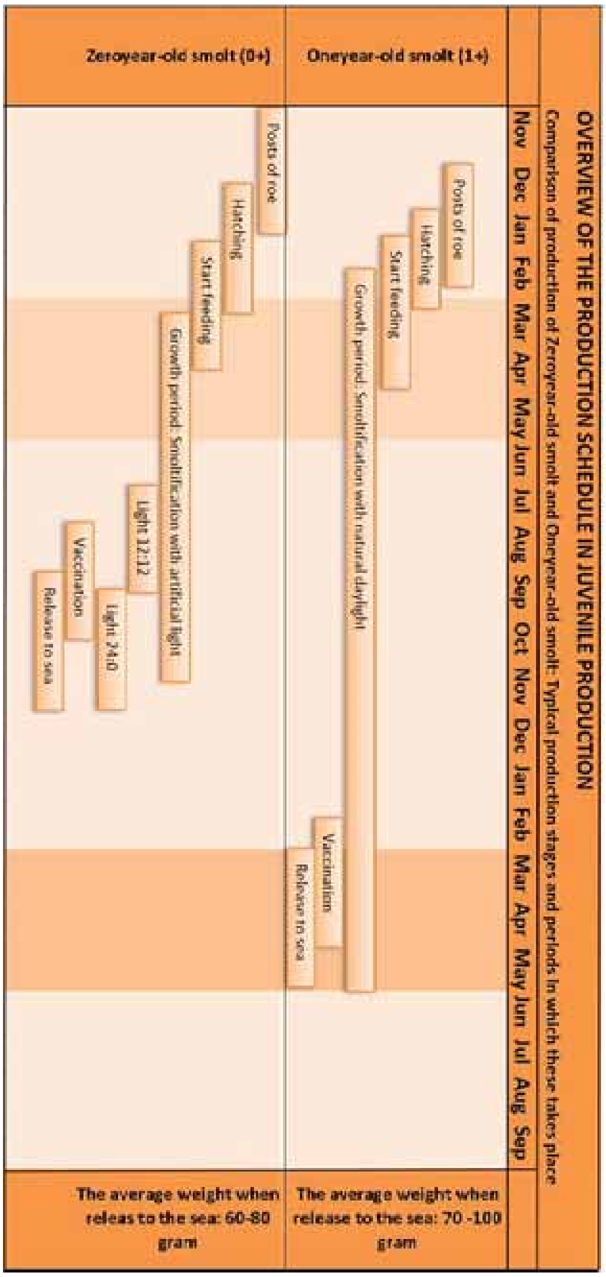

Figure 5: Overview of the production schedule in juvenile production.

Figure 4 and Figure 5 gives illustrates that the innovations in smolt production have led to a faster production process and earlier release for smolt. Earlier smoltification and increased growth due to new technology and innovations has given a higher degree of flexibility and utilization of the capacity for both the land-based production and the grow-out farms. As such, the technological progress in juvenile production have contributed to a better competitiveness for the whole Norwegian Salmon industry.

4 ABSTRACTS OF THE PAPERS

In the following, I provide a brief description of the thesis‘s four papers.

4.1 *Paper 1*

Innovation and Productivity Growth in Norwegian Production of Juvenile Salmonids.

A number of studies have documented a rapid productivity growth and a decline in production cost in Norwegian salmon farming. However, little attention has been given to productivity growth of the input factors. Two thirds of the reduction in costs that has taken place in Norwegian salmon grow-out farming can be attributed to better and cheaper inputs. If one is to obtain a better understanding of the factors that enhance the productivity and competitiveness of salmon aquaculture, it is important to study the development of the suppliers. This paper provides an analysis of productivity growth for one key input factor in salmon farming, juvenile salmon.

This issue is addressed by the use of conventional econometric methods were we construct translog cost functions. The dataset is an unbalanced panel data set with 1802 observations. We have access to 23 years of firm level data from 1988 to 2010 from the Norwegian Directorate of Fisheries. The data set contain 70-115 hatcheries yearly out of a total population of 190-260 producing units. Our econometric analysis has allowed us to identify the role of technical change for cost reduction.

We find that the industry has experienced an annual average rate of technical progress of 4.1 % over the period 1988-2010. However, the rate of technical progress has slowed down the recent years. For the years 2006 - 2010, the technical progress has been < 1 %, suggesting that the industry is struggling to innovate at a rate that can provide lower production costs. A substantial part of the cost savings due to productivity increase in juvenile production is passed on to the grow-out farms in the form of lower prices, as this makes Norwegian salmon aquaculture products more competitive relative to other food producers.

4.2 *Paper 2*

Econometric Modeling of Technical Efficiency in Norwegian Production of Juvenile Salmonids.

A key feature for the cost reduction in Norwegian salmon farming has been better and cheaper inputs. Earlier analysis of juvenile farming has indicated that a substantial technological progress has taken place during the period 1988-2010. Furthermore, it is also found that the productivity growth is slowing down the recent years. This may suggest that the industry is struggling to innovate at a rate that can provide lower production costs.

In the hatchery sector, production technology and production practices vary between plants. The industry is currently more heterogeneous than in the earlier years. The heterogeneity in terms of production technology indicates that production practices vary between plants and the industry is currently more diversified and heterogeneous than in the earlier years. These differences can lead to different levels of efficiency. For producers to stay competitive, it is necessary and sufficient that they are technically efficient in the production process. Failure to achieve this will give weaker economic performance, because technically inefficient firms use more inputs than necessary to produce a given quantity of output. Furthermore, inefficiency in smolt production will directly lead to higher costs for the grow-out farms.

In this paper, we investigate technical progress with a particular focus on technical efficiency for the juvenile salmon producers in Norway. The production technology is estimated using a translog production function. We use the stochastic frontier method, which account for inefficiency, in this study. Like for Paper 1, we use public collected data offered by the Norwegian Directorate of Fisheries for the estimations. For this particular study, the dataset is extended by two years (1988-2012).

The sample mean rate of TC is found to be 6.5 % yearly. The estimate indicates that the hatcheries have produced 6.5 %

more smolts every year because their production technology has become better. Our results indicate that technical inefficiency is present between both regions and firms. The mean firm inefficiency is found to be 12.3 %. This is inefficiency caused by operational factors as accidents, escapes and deceases or different firm specific efficiency. The mean inefficiency caused by region specific effects is found to be 10.6%. This inefficiency is most likely caused by variations in the temperature of the inlet water and other differences in biophysical conditions. Our results suggest the southernmost regions are more effective than the northernmost ones. We found a total yearly inefficiency in juvenile farming of 22.9% on average, or that the average firm is 77.1% efficient. This indicates that there is a potential for improvement in efficiency in the industry. This will augment productivity growth in increasing competitiveness.

4.3 *Paper 3*

Learning-by-doing or Technological Leapfrogging: Production Frontiers and Efficiency Measurement in Norwegian Farming of Juvenile Salmonids.

In the literature of economic growth and innovative industries, there are different perspectives on what provides the most efficient firm. Two different theories that explains technological efficiency and productivity in an industry are learning-by-doing and technological leapfrogging. The learning-by-doing theory explains different productivity level in that incumbent firms benefit from more experience. The concept of technological leapfrogging implies that firms entering innovative industries may be able to leapfrog incumbent firms by bypassing heavy investments in older technologies. This will makes them more efficient than the existing firms.

The purpose of this paper, is analyzing the potential existence of learning-by-doing and technological leapfrogging effects in the production of juvenile salmonids. The aim is to gain a more comprehensive understanding of the productivity by modelling the effect of the age of the firm on efficiency explicitly. For the econometric estimations, the stochastic frontier method is used and a stochastic cost frontier analysis is performed. The hatchery panel dataset on firm level from 1988-2012 is used to investigate how the age of the firm affect the technological efficiency.

The analysis indicate that the age of the firm has a positive impact on the efficiency, and that inefficiency therefore decrease with the age of the firm. The results indicate that during the first 15 years of production, the hatcheries will experience a positive effect of learning-by-doing. After turning 15 years of production, the expected inefficiency will increase. Hence, the analysis find econometric support for the existence of a learning-by-doing effect in juvenile production. This means that firms will benefit from learning-by-doing and experience. As inefficiency is estimated to decrease with age, existing firms are found to be more technological efficient than the newcomers.

4.4 *Paper 4*

Salmon Production: Larger Companies and Increased Production.

In the productivity literature of salmon farming, it is well known that innovations and productivity growth are the main sources for the successful development. Despite the fact that several companies have grown very large due to mergers and acquisitions, less attention has been given to the company size in this industry.

In this paper, we look closer at the potentially important factor in further global production growth, development of company size. Globally, Atlantic salmon is produced in significant quantities in only a handful of countries. The five largest countries is Norway, Chile, Scotland, Canada and the Faroe Islands. Norway had a production share of 51 % in 2010, Chile 28 %, Scotland 7.4%, Canada 5.7% and Faroe Island 2.7%.

We have access to data on the number of companies in each of the five leading salmon producing countries that make up for 80 % of the production for every third year from 1997 to 2012 from Kontali Analyse and Nordea Bank. This data allows us descriptive insights in the development in concentration over time. In addition, we construct a formal concentration measure for the year 2010 using data provided by Nilsen and Grindheim (2011). This dataset allow us to create a Herfindal-Hirchman Index (HHI) for each of the five producing countries, as well as for the industry globally.

Our results shows that there is a general tendency towards fewer but larger companies in this industry. A clear consolidation process has been present in all the five producing countries from 1997 to 2010. The HHI analysis for 2010 indicate that globally, salmon production is not very concentrated. Moreover, in the two largest production countries, Norway and Chile, the concentration level is also very moderate. The concentration level is higher but still moderate in Canada and Scotland, and high in the Faroe Islands. It is interesting to note how the concentration level increases for the producer countries with lower production levels. However, given the global nature of the salmon market, there is no reason to expect that this concentration give those producer countries with lower levels of production any opportunity to influence prices. Rather, given that the observed companies make up more than 75% of total production, the concentration in the smaller producer countries seems to be an indication that a relatively large company size is beneficial when targeting the main markets for salmon.

It seems clear that farm size has been important for the production growth in this industry. Advantages seems to be big in the purchase of services, the production and in marketing and sales, and that the existence of larger companies has helped the salmon industry to grow. Although this study indicates that larger companies have advantages, it should be noted that the concentration level is low in the largest producing countries and that the industry is very heterogeneous when it comes to company size. As there is a global market for salmon, there is accordingly no reason for concerns with respect to the competitiveness of the industry.

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PART II

List of papers

Paper I

Sandvold, H. N., & Tveterås, R. (2014). Innovation and Productivity growth in Norwegian Production of Juvenile Salmonids. *Aquaculture Economics and Management, 18, 149-168.*

Paper II

Asche, F., Sandvold, H. N., & Tveterås, R. (2014). Econometric modeling of Technical Efficiency in Norwegian Production of Juvenile Salmonids. *Submitted to Marine Resource Economics.*

Paper III

Sandvold, H. N. (2015). Learning-by-doing or Technological Leapfrogging: Production Frontiers and Efficiency Measurement in Norwegian Farming of Juvenile Salmonids. *Submitted to Aquaculture Economics and Management.*

Paper IV

Asche, F., Roll, K. H., Sandvold, H. N., Sørvig, A., & Zhang, D. (2013). Salmon Production: Larger Companies and Increased Production. *Aquaculture Economics and Management, 17 (3), 322-339.*

Paper I

INNOVATION AND PRODUCTIVITY GROWTH IN NORWEGIAN PRODUCTION OF JUVENILE SALMONIDS

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ABSTRACT

The literature to productivity growth in the grow-out phase for salmon has given substantial attention, while little attention has been given to productivity growth of the input factors. This is despite the fact that a number of innovations have improved quality reduced prices for many input factors, contributing to the competitiveness of the industry. This paper provides an analysis of productivity growth for one key input factor in salmon farming, juvenile salmon. We estimate translog cost functions on salmon hatcheries for the period 1988 to 2010. The econometric analysis shows that innovations and productivity growth have led to a reduction of unit costs in production of salmon juveniles, particularly at earlier stages, but the rate of technical progress has declined in recent years.

KEYWORDS

Salmon aquaculture, juvenile production, technical change, productivity, translog cost function.

1 INTRODUCTION

The Norwegian salmon industry has been a success story, as production has increased from a few thousand tons in 1980 to over 1.2 million tons in 2012. This development has been possible due to a strong productivity growth which has reduced production costs and improved competitiveness (Asche, 2008; Asche, Roll, & Tveterås, 2009). A number of studies have documented a rapid productivity growth and a decline in production cost in Norwegian grow-out farming (Andersen, Roll, & Tveterås, 2008; Asche, 1997; Asche & Bjørndal, 2011; Asche, Guttormsen, & Nielsen, 2013; Asche, Guttormsen, & Tveterås, 1999; Asche, Roll, & Tveterås, 2007, 2009; Bjørndal & Salvanes, 1995; Guttormsen, 2002; Kumbhakar & Tveterås, 2003; Roll, 2013; R. Tveterås, 1999; R. Tveterås & Battese, 2006; R. Tveterås & Heshmati, 2002; Vassdal & Holst, 2011). This has been possible due to improved input factors and increased control over the production process (Anderson, 2002; Asche, 2008). Furthermore, there are evidence of economies of scale at the farm and firm level (Roll, 2013). In addition, demand growth (Asche, Dahl, Gordon, Trollvik, & Aandahl, 2011), changes in industry structure and productivity growth in the supply chain (Kvaløy & Tveterås, 2008; Larsen & Asche, 2011; Olson & Criddle, 2008) has also contributed to increased production.

Tveterås and Heshmati (2002) reported that two thirds of the reduction in costs that has taken place in Norwegian salmon grow-out farming can be attributed to better and cheaper inputs, and Asche (2008) indicated that a substantial productivity development seems to take place among input providers. Hence, if one is to obtain a better understanding of the factors that enhance the productivity and competitiveness of salmon aquaculture, it is important to study the development of the suppliers. However, productivity growth at this stage of the industry has received little attention for all aquaculture species.

In this paper productivity development in Norwegian juvenile production will be investigated. The slaughter-ready farmed salmon is raised in floating cages in the sea, but this is after an initial period in land-based freshwater farms, often called hatcheries. Juvenile production includes production of fry and smolt[1]. The fish are transferred into salt water pens at a weight of 60-100 gram. Smolt is the input factor that has the greatest cost share after feed. In 2010 the costs of the smolt represented 12 % of the total costs, down from 25% in 1985. The supply and cost of smolt is a critical element for the cost reduction in the grow-out plants and has not been the focus of the earlier studies of productivity growth in salmon aquaculture.

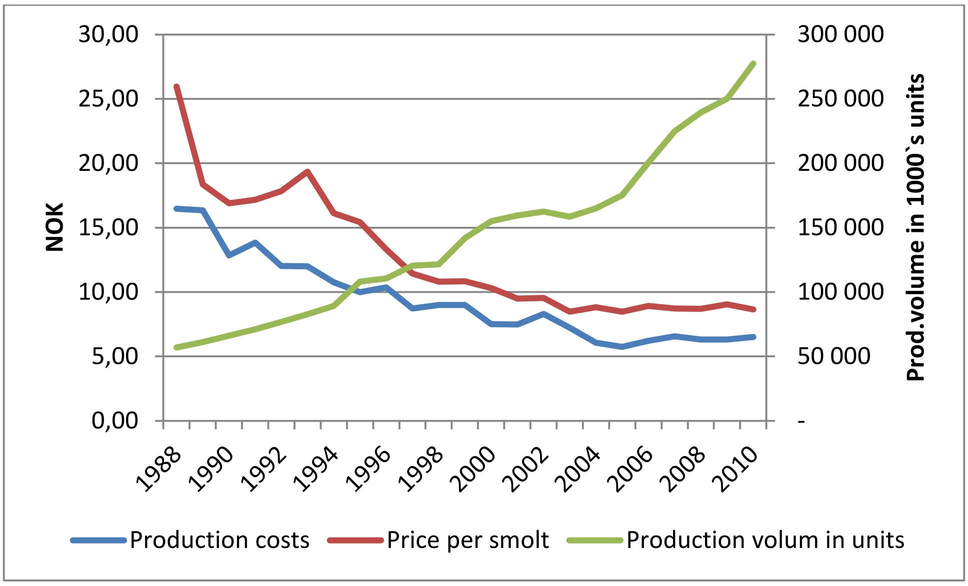

Figure 1. Total production of smolt and the associated prices and costs in the Norwegian salmon industry in the period of 1988 – 2010. Source: Norwegian Directorate of Fisheries.

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[1] Fry is sold to other hatcheries for further growth in fresh water and smolt is sold to grow-out farms for further growth in salt water. In 1988, 38 % of the hatcheries sold both fry and smolt. In 2010, the number of hatcheries that sold both fry and smolt was reduced to 27 %. Hence, smolt is the main product of interest for the hatcheries.

Figure 1 provides evidence of important developments which have taken place in juvenile production during the period 1988-2010[2]. The production volume measured in numbers of smolts in 2010 was nearly five times higher than in 1988. In 1988 the hatcheries in Norway produced 57 million smolts while in 2010 the production was 280 million smolts. This is largely as expected as the smolt production must increase to enable the increased salmon production during the last two decades. The increased production has been accompanied by a substantial reduction in the unit production cost and real sales price. In 1988 the real production costs were around 16 NOK per unit, while in 2005 it reached its lowest reported level at less than 6 NOK. Since 2005, the unit production costs have been fluctuating. From 2008 there has been an increase in the real sales price, and in 2010 it was close to 7 NOK per smolt.[3] The cost reduction is an indication of the technological change that has taken place, but also that technological progress may have been higher in earlier years. The real sales price per smolt also experienced a clear downward trend in the period. In 1988 the sales price was around 26 NOK per unit and in 2010 it had decreased to 9 NOK. Hence, it is clear that lower smolt prices have contributed to lower cost for the grow-out plants. As for the salmon grow-out farms, there is also a close relationship between the trend in production cost and price (Asche, 1997), indicating a competitive industry.

Figure 1 gives an interesting overview of the development of costs and prices. Nevertheless, it does not provide any direct information of the underlying rate of productivity growth or the level of technical change. The fact that we see an increase in the average production costs from 2005 suggests that a slowdown in productivity growth may have taken place in

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[2] It is not possible to separate costs directly related to the number of sold fry. This means that the costs per unit of fish presented in Figure 1 are all costs related to produce smolt, including the fry.

[3] Price variability is substantial also for smolt, but no tool to handle price risk has been developed as has been the case for the grow-out farms (Oglend, 2013; Oglend & Sikveland, 2008; Solibakke, 2012)

this industry during the latest years, which is also in parallel to what has been observed for the grow-out farms (Asche, Guttormsen, & Nielsen, 2013; Vassdal & Holst, 2011). In this paper we will analyze the factors driving the productivity growth in juvenile production, with particular focus on technological change. The productivity growth and the technical change will be estimated using a translog cost function.

This paper is organized as follows. In section 2 we provide a brief description of the biological production process, followed by a presentation of the industry in section 3. In section 4 we discuss the technological development in this production, before an overview over the cost composition and cost structure development in juvenile production is given in section 5. In section 6 we present the Norwegian salmon hatchery dataset used in this survey. The econometric specification of the model will be provided in section 7, before the empirical results are reported in section 8 before concluding remarks are provided.

2 JUVENILE PRODUCTION IN NORWEGIAN SALMON FARMING

Salmon are brought to the hatcheries as fertilized eggs[4]. This has usually taken place in the period from November to February in one, two or three rounds depending on the size of the production. There has been an extension of the roe season in recent years. Currently, nearly 50 % of the hatcheries get their eggs delivered as early roe in the period from October to December, and the remaining 50 % get their eggs in the period from December to March. When the roe is hatched the fry is biologically endowed with a yolk-sac and will be nourished by this for the first month. After roughly 4 – 6 weeks the fish is transferred from the hatching

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[4] The farming of brood stock and production of offspring are done at separate locations. Large companies have their own units for breeding and brood stock, but smaller independent hatcheries still buy the roe from external suppliers.

tanks to larger units, and the feeding will start. During this period the water temperature and oxygen levels are controlled for optimal growth conditions.

When the fry starts on dry feed they grow quickly, and at about 5 gram they will be transferred to outside tanks [5]. This usually takes place in the period from April to May. Now the fry will live in naturally tempered freshwater until it reaches the smoltification stage and becomes ready for saltwater. This normally happens the spring after it is hatched. Through size grading, the farmer ensures that the fish are of optimal and uniform size and weight to provide the best possible growth-rate. The freshwater environment is monitored for oxygen and pH – values. In addition, licensed veterinarians and fish health technicians regularly check the health of the salmon.

Progressively, the juveniles undergo the biological changes that prepare them for life in saltwater as smolts. This process leads to both internal and external physical changes. First, it becomes a *parr*. At this stage the fish is characterized by vertical and dark bands at the sides known as the parr-marks. In addition, the fish undergo a hormonal change that makes it able to adopt the correct amount of salt using the gills. As the process progress, the skin turns silver and the parr-marks disappear. The fish usually becomes a smolt at a weight of 60-100 gram. Artificial light is used to control and accelerate the smoltification process.

Prior to saltwater entry the fish are vaccinated to ensure it is able to fight off common pathogens found in the marine environment. Finally, after 9 - 18 months in fresh water the salmon are transferred to sea using well-boats. During the journey the salinity of their water is gradually increased to approach the saltwater.

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[5] Some of the new hatcheries have all their production facilities indoors.

3 INDUSTRY SECTION AND REGULATION

As for the grow-out farms, the production of juveniles is highly regulated, and one needs a government license to produce. Juvenile production has traditionally been restricted by maximum number of units that can be produced each year, and maximum production varies by farm depending on different environmental concerns. The requirements that have to be satisfied to obtain a juvenile license include access to a sufficient supply of fresh water, prevention of escapees, safe discharge of waste water, as well as health, environment and safety requirements for the employees.[6] The size of the fish in the hatcheries has been restricted to maximum 250 gram.

Legislation and regulations for fresh water production have changed from the industry started up in the late 1970`s, but not dramatically. Recent licenses will not be given a restriction in number of units produced, but in maximum withdrawal of freshwater and maximum discharge of wastewater. As such, one is moving towards a system that more explicitly address the environmental externalities. Nielsen (2011, 2012) provides analysis of how more efficient regulations with respect to discharges can lead to higher production per unit of discharge. Furthermore, the ministry has recently been given the right to grant an exemption to extend the juvenile phase in closed land-based systems until the fish reaches a size of up to 1000 grams[7]. Production of salmon with extended land phase could lead to further restructuring and technological changes in the salmon industry.

In 1988 there were 263 licenses for production of salmon and trout juveniles in Norway. Producers could have a majority share in only one license each, and the license could vary in

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[6] Chu et al (2010) provide a more general discussion of the impact of regulations for the development of aquaculture.

[7] This is a pilot project from the 1st of May 2012.

size from production of 10 000 units to maximum 1.5 million fish yearly. In 2010 there were 213 licenses, and the majority of the hatcheries have more than one license. There are some hatcheries with 4 to 7 licenses, and the largest one, owned by Marine Harvest, operates 29 licenses for juvenile production.[8] As of 2012, the production volume of the hatcheries varies from 90.000 units per year up to 50 million units each year. The latter is the government's maximum allowed production quantity for one company with multiple licenses.

As for the grow-out farms, there has been a trend of consolidation into fewer and larger companies also in the hatchery sector[9]. At the same time, the average production per hatchery has increased substantially. In 1988, the average production per hatchery was 309 000 units, and in 2010 it had increased to 2.2 mill units. Increased automation and centralized management have also led to larger production volume per person employed, and thereby to increased labor productivity. In 1988 the industry produced 88 000 units of fish per employee, and in 2010 the production was increased to 413 000 per person. If we look at the employment rate, the average number of employees per plant increased from 3.5 in 1988 to 6.8 in 2010.

One reason for the structural changes in the industry, with a trend towards fewer and larger firms, is caused by changes in the legislation for aquaculture in Norway. Until 1991, majority ownership interests in more than one salmon farm in general was prohibited. In 1991 the law was changed and the ownership restriction was in reality not in effect any longer. Since then, more and more firms are becoming vertically integrated from production of broad

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[8] Marine Harvest is Norway's and the world's largest salmon producer. The organization produce more than 20 % of all Norwegian salmon as well as more than 20 % of all Atlantic salmon globally (Asche, Guttormsen, & Nielsen, 2013).

[9] Hence, several of the arguments provided by Asche et al (2013) in the case of grow-out plants also seem to apply here. However, the plants are still well spread out, and as such, the risk diversification arguments of Oglend & Tveteras (2009) also apply here.

stock to the grow-out farms. The industry has become more heterogeneous when it comes to size during the period.

The majority of the hatcheries were built in the 1980`s and there has been few new plants during the last 30 years. Improvement and development of existing facilities have been the main reason for increased production. In 1988 all hatcheries used a similar technology, the *flow-through-system.* Today most of the hatcheries have *semi-closed-systems* with some reuse of the inlet water.

4 INNOVATION AND TECHNOLOGICAL DEVELOPMENT IN JUVENILE PRODUCTION

Technological development in juvenile salmon production has been extensive from open pond-systems to the current closed or semi-closed production systems with a high degree of control. We will here review this development from the industry's first steps more than 30 years ago until today's large scale and technologically more advanced production units.

Among the most important changes is the fish itself. A breeding program for Atlantic salmon and rainbow trout started in the early 1970s (Gjedrem, 2005), focusing first on more rapid growth, and then a group of objectives including resistance against specific diseases and flesh quality. The breeders used genetic strains from several river systems in order to establish a selective breeding program, with selection taking place at the family as well as the individual level. Two attributes that are particularly emphasized are the ability to be efficient and robust. Efficient attributes include good production and quality benefits as growth, color, fat content and body shape. Robust attributes mean good health properties as resistance against specific diseases, reduced deformities and reduced early sexual maturity. Genetic innovations have contributed to reduction in the production time, improved feed efficiency, better survival and improved meat quality.

Improved fish health through vaccination is among the most important measures to prevent spread of diseases. Vaccines for salmon were first developed in the late 1980s, which led to a huge reduction in the use of antibiotics (S. Tveterås, 2002). The juveniles are vaccinated routinely against diseases such as furunculosis, vibriosis, coldwater vibriosis, winter wounds and IPN.[10]

In nutrition and feed formulation there have also been radical innovations. Important milestones within the fish feed development have been the transition from wet feed to the dry feed, the use of granulated pellets, autoclaving and the production of micro-pellet for the juveniles. The food has gradually become better adapted to the fish`s true nutritional needs. In addition, one can also get feed specially constructed for recycling water technology and preventive health feed.

Several technological innovations have influenced the production process, with the use of artificial light one of the most important. Daylight has an important impact on the life of salmonids, and for juveniles the photoperiod influences the smoltification process. The industry started to experiment with artificial light at the end of the 1980s to extend the smoltification period[11]. Artificial light is installed on the edge of the tub, and is usually used in six – seven weeks before the transfer to the sea. As a result of the artificial light the hatcheries usually carry more than one generation of fish in the farm within a year. The *zero-*

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[10] Asche (Asche, 1997) shows how diseases can have cost consequences on the scale of the industry, and Asche, Roll and Tveterås (Asche, Roll, & Tveterås, 2009) and Hansen and Onozaka (Hansen & Onozaka, 2011) discuss the consequences of the recent disease crises in Chile.

[11] This is a main reason why the supply of Atlantic salmon is more evenly distributed over the year than coho and salmon trout, as one is not able to influence the smoltification process for these species. This may also be an important factor in explaining why the share of Atlantic salmon production is increasing in salmonid aquaculture (Asche, Roll, Sandvold, Sørvig, & Zhang, 2013).

year-old smolt is transferred to the sea the autumn after hatching, and the *one-year-old* smolt is released the second spring after it is hatched. Earlier smoltification and increased growth due to new technology and innovations gives a higher degree of flexibility and utilization of the capacity for both the land-based production and the grow-out farms[12].

The production of juveniles requires supply of large quantities of fresh water. Despite the presence of abundant fresh water resources[13], the amount that can be used for aquaculture is strictly regulated. Innovations in recycling of water are therefore highly relevant in land based production. The water recirculation technology called Recycling Aquaculture System (RAS), which reduces the demand for water dramatically, is increasingly replacing the traditional flow-through systems. Water recycling involves the removal of particles, nitrogenous metabolites and carbon dioxide, as well as the addition of new oxygen. Particles are removed with mechanically filters or sludge basins, carbon dioxide are vented while metabolites usually are removed by biological filtration. The technology also allows higher degree of control of critical growth factors such as temperature and water quality, as well as environmental risk factors as escapes and polluted water spills are minimized. The RAS technology was first introduced in Norway in 2006, and has gradually been developed and taken into use the last years. In 2012 23 hatcheries out of a population of 173 use the RAS technology.

The equipment used in juvenile production has become more efficient, with higher speed (e.g. feeding and sorting machines) and larger volumes. The sizes of the tanks used in the production have increased steadily at the same time, contributing to larger facilities. These

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[12] Optimal rotation and effective use of capacity is becoming more and more important in grow-out farms because the production systems are becoming more expensive.

[13] Abundant water resources could be the reason why the recirculation technology was introduced later in Norway compared to other countries as Denmark and the USA.

changes have led to operations that are physically less demanding for the employees and more careful handling of fish.

5 COST SHARE DEVELOPMENT

Innovations have largest impact when they occur for the most important input factors in terms of cost shares. In Table 1, the cost composition for juvenile production in 2010 is shown. In contrast to what is the case in the grow-out phase with feed representing 50 % of total costs (Guttormsen, 2002)[14], there is no dominant cost factor for the hatcheries. The costs are relatively evenly distributed between inputs such as operating expenses, salary, roe, vaccine and feed, while costs associated with electricity, depreciation, interest and insurances are somewhat lower. The industry is more labor intensive than grow-out farms, as the labor share makes up for 20 % of the total costs.

Table 1. Production cost shares for different input factors in 2010. Source: The Norwegian Directorate of Fisheries.

Cost item	Cost share
Operating expenses	20.21 %
Salary	19.75 %
Roe	17.22 %
Vaccine	14.86 %
Feed	12.06 %
Depreciation	7.88 %
Electricity	5.44 %
Insurance	1.30 %
Interest	1.28 %

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[14] Influencing flesh colour using of astaxanthin that makes up over 10 % of the feed cost in grow-out farms (Forsberg & Guttormsen, 2006) is not done in juvenile production. Torrissen et al (2011) provide a more general overview of feed ingredients.

Figure 2 shows the development of the cost shares for the period 1988 to 2010. The only significant change is the rapid increase in the other operating expenses category in the early years. This is largely explained by the fact that vaccine was not established as a separate cost category before in 1997, and vaccines has continued to increase its cost share. Expenses like interest payments and insurances have been substantially reduced.

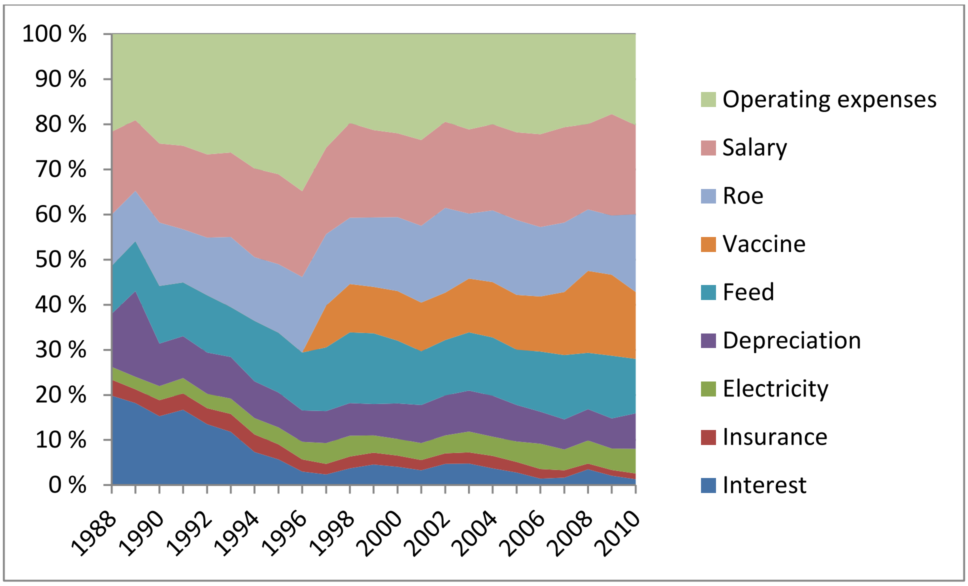

Figure 2. Cost shares in Norwegian juvenile salmon production from 1990 to 2010. Source: Norwegian Directorate of Fisheries.

Otherwise, the cost shares are relatively stable, suggesting a largely input-neutral technological development on the assumption of limited changes in relative prices. It is worthwhile to note the relatively low and stable cost share for feed, in contrast to the development for grow-out farms. For grow-out farms have the development been technologically non-neutral as the feed share has grown largely[15] .

6 DATA

The dataset used in this study is an unbalanced panel data set with 1802 observations. We have access to 23 years of firm level data from 1988 to 2010 from the Norwegian Directorate of Fisheries. The data set contain 70-115 hatcheries yearly out of a total population of 190-260 producing units. The Norwegian Directorate of Fisheries annually requests information on production, economic and financial variables, which the farmers by law are required to return.

The data reported are information on production, costs and revenues. Some of the variables included in the data set are firm identification code (name, region and county), type of ownership, year of establishment, costs (roe, feed, insurance, salary, labor, electricity, vaccine, net interest expense and other operating expenses), revenues (sold number of fry and smolt[16], compensation for loss), assets and liabilities, production (in units), stock of fish in tanks at the beginning and end of the year (in units), employment in full-time equivalents (FTE) and hours of labor, number of licenses and license volume, etc.

Following the procedures of previous econometric studies of salmon farming, such as Tveterås (R. Tveterås, 1999) we construct output levels as well as input levels and prices from the farm data set. We define production *(y)* as the actual number of fry and smolt sold

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[15] From 1986 to 1996 the cost share of feed increased from 27 % to approximately 50 %. In the period from 1996 to 2008 the use of feed has been relatively constant (Asche, Guttormsen, & Nielsen, 2013).

[16] The hatcheries do not report the weight of the sold fish (only number of units sold) on the questionnaire. However, industry sources indicate that the average weight of a smolt has not changed very much. The increased growth has primarily lead to earlier release time and thereby increased production capacity.

each year, plus the change in stock from the beginning of the year to the end of the year. The quantity sold is corrected for mortality, but there are dynamic aspects of juvenile production based on the biology, which influence the production output *(y)*. First, one normally has at least two cohorts of fish in the hatcheries. Hence, the total production consist both of units sold as well as change in the stock during the year. Second, some of the firms included in the survey in additional to the main product smolt also sell fry due to capacity constraints. The majority (64 %) of the firms in this survey has only one output, the smolt, but we have nevertheless chosen to use both units as output (*y)*. The output (*y)* includes smolts of both salmon and trout because this is not separated on the questionnaire to the Directorate of Fisheries. One can argue that in juvenile production the output level is exogenously constrained due to the size of the license given by the authorities.

Juvenile production requires four important input factors; roe, feed, labor and capital. In the empirical analysis in this study, only three input factors will be implemented in the production function: fish feed, labor and capital. Roe is omitted because price information is not available. Moreover, we do not include a separate variable for vaccines as this information is not available in the early years of the data set. In addition, from the late 1990s most smolts are vaccinated. For the variable feed, only data on total expenditure and the value of inventory at the end of the year are available in the dataset and we have to construct prices for feed. As is well known, fishmeal and fish oil are main ingredients in fish feed (Asche, Oglend, & Tveterås, 2013; S. Tveterås & Tveterås, 2010) and we therefore use these prices in addition to dummies for year and counties, to predict the farm level feed prices. For labor, the price (hourly wage rate) is calculated as the annual wage expenses divided by paid working hours. The data set give us information of both hours of paid and unpaid working hours at the hatcheries, which we use to construct a new measure of labor costs using the calculated farm wage rate as opportunity cost for the unpaid hours. The last variable, capital, is measured as an index of the capital flow of the different capital items divided by total capital. The flow of services was calculated as a user type including depreciation based on replacement costs and current interest rate. The interest rate was set to 7 %. This represents the discount rate for public investments in Norway. All the nominal costs and prices are deflated by the consumer price index (CPI).

7 ECONOMETRIC SPECIFICATION

A firm's technology can be represented by a production function, given in its most general form as $y = f(x, t)$, where y is output, $f(\cdot)$ represents the technology, x is a vector of inputs (feed, labor, capital, etc.) and t is a time trend variable or a vector of time dummy variables representing technological change. As the juvenile industry is competitive and the produced quantity restricted by the license, it is reasonable to represent the producer as cost minimizers. Thus, the long-run cost function is $C = C(w, y, t)$ where C is cost in NOK, w is vector of factor prices. With the inputs we have price data on – feed (F), labor (L) and capital (K) - the cost function in juvenile production can be specified as $C = C(w_F, w_L, w_K, y, t)$.

We will use a translog[17] cost function to describe the technology. The translog long run cost function is given as:

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[17] A non-parametric method like the Total Factor Productivity (TFP) index could also have been used to investigate this issue. There are two reasons for choosing the parametric approach. First, The TFP approach is deterministic, and as salmon farmers are exposed to shocks from biophysical factors, allowing for stochastic noise seems appropriate. The error term in the model allowed for statistical noise as temperature, light and diseases. Second, the dataset gives information of prices and costs, which means that we are able to use a specific functional form representing the production process. Follow this, the technical change gives an estimation of the productivity after adjusted for the prices.

$$\ln C = \alpha_0 + \sum_i \alpha_i \ln w_i + 0{,}5 \sum_i \sum_j \alpha_{ij} \ln w_i \ln w_j + \alpha_y \ln y + 0{,}5\alpha_{yy} (\ln y)^2 + \sum_i \alpha_{iy} \ln w_i \ln y + \alpha_{FRY} D_{FRY} + \alpha_{y,FRY} D_{FRY} \ln y + \sum_i \alpha_{wi,FRY} D_{FRY} \ln w_i + \sum_t \alpha_t D_t + \sum_t \sum_i \alpha_{it} \ln w_i^* D_t + \sum_t \alpha_{yt} \ln y^* D_t + u$$

were D_t is a vector of time (year) dummy variables (t = 1988,…, 2010), w_i are the inflation-adjusted price of input *i*, D_{FRY} is a dummy variable for firms that also produced fry in addition to smolt, α are parameters to be estimated and *u* is the stochastic error term.

The model is estimated by Zellner's Seemingly Unrelated Regression Estimator (SURE) due to the correlations between the error term in the cost function and the cost share equations. The Cobb-Douglas is a special case of the translog cost function with all the second order parameters restricted to zero. We perform a Likelihood ratio test of the translog vs. the Cobb-Douglas. The LR test statistic is 118.6, implying that we can reject the Cobb-Douglas at all conventional significance levels. From the cost function presented above one can derive returns to scale, ($RTS = 1 / (d \ln C / d \ln y)) = 1 / (\alpha\ y + \alpha\ yy * \ln y + \sum_i \alpha\ cy * \ln w_i + \alpha_{y\ FRY} * D_{FRY} + \sum_t \alpha_{yt} * D_t$). The conditional own price elasticity of demand for input is defined as $E_i = (\alpha_{ii} + S_i^2 - S_i)/S_i$ (i = feed, labor, capital) were S_i is the cost share of input *i*.

When studying productivity development over time, a central measure of interest is the rate of technical change. The rate of technical change (TC) is our measure of how innovations and other factors influence productivity growth, as it is not possible to observe variables that measure impact of innovations and the adoption of these directly. The rate of technical change from year t-1 to year t is specified as:

$$TC = (\alpha_t - \alpha_{t-1}) + \sum_i ((\alpha_{it} - \alpha_{it-1}) \ln w_i) + (\alpha_{yt} - \alpha_{yt-1}) \ln y$$

where the first term on the right-hand side of the equation is "pure" or neutral technical change (in the sense that it is not scale- or input-biased), the second term is input-biased technical change and the third term is scale-biased technical change. The input-biased technical change shows the effect of technical change on productivity associated with input levels, and the scale-biased technical change shows the effect of technical change on economies of scale.

In a biological production sector such as salmon farming the empirical estimate of TC will be influenced by biophysical shocks such as diseases and temperature variation, and it is therefore possible to obtain negative rates of technical change.[18] If there is technical progress and no "noise" from biological shocks or other shocks the cost based TC measure is negative.

8 EMPIRICAL RESULTS

The estimated coefficients of the translog cost model are available in the Appendix. The Appendix also shows the model's R^2. The pseudo R^2 is high; the adjusted R^2 has a value above 0.99. The pseudo R^2 of the feed and labor cost share equations are 0.89 and 0.95, respectively.

Table 2 present the estimated elasticity's from the model. The estimated return to scale (RTS) is 1.19. This indicate that farms operate at a level of inputs where there are still increasing returns to scale. It is similar to what has been reported in recent studies of the grow-out industry (Asche & Roll, 2013; Asche, Roll, & Tveterås, 2009; Roll, 2013). Increasing returns may not be surprising, since farms are restricted on the output side by government regulations, but provides an indication that there is still scope for increased scale-efficiency.

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[18] Guttormsen (2008) discusses how growth is a function of temperature, and Hermansen and Heen (2012) discuss how larger temperature changes influence salmon production.

In addition, table 2 also shows the own price elasticity's. The own price elasticity of feed, labor and capital input demand are all negative, and is significantly different from zero.

Table 2. Own-price Elasticity's evaluated at sample mean values for cost model estimated by Seemingly Unrelated Regression.

Elasticity	Estimate	Standard error	t-value	P-value
RTS	1.119	0.141	7.92	0.000
E_{feed}	-0.766	0.206	-37.15	0.000
E_{labor}	-0.501	0.010	-49.94	0.000
$E_{capital}$	-0.784	0.139	-5.61	0.000

Next, we turn to the issue of primary interest, the rate of technical change (TC) over time. Table 3 present estimated TC from the restricted costs model. The "pure" technical change (TC_{pure}) which is not related to inputs and scale, contributes most to the technological progress. TC_{pure} has an estimated average sample rate of – 0.206 and is significantly different from zero. Both the components associated with inputs (TC_{factor}) and scale (TC_{scale}) contributes negatively, with estimated average sample rates of 0.0204 and 0.141, respectively. The TC_{scale} is significantly different from zero, while TC_{factor} is not. The sample mean rate of technical change (RTS) is -0.0415, and is significantly different from zero. This gives a mean rate of technical progress of 4.1 **%** for the entire data period.

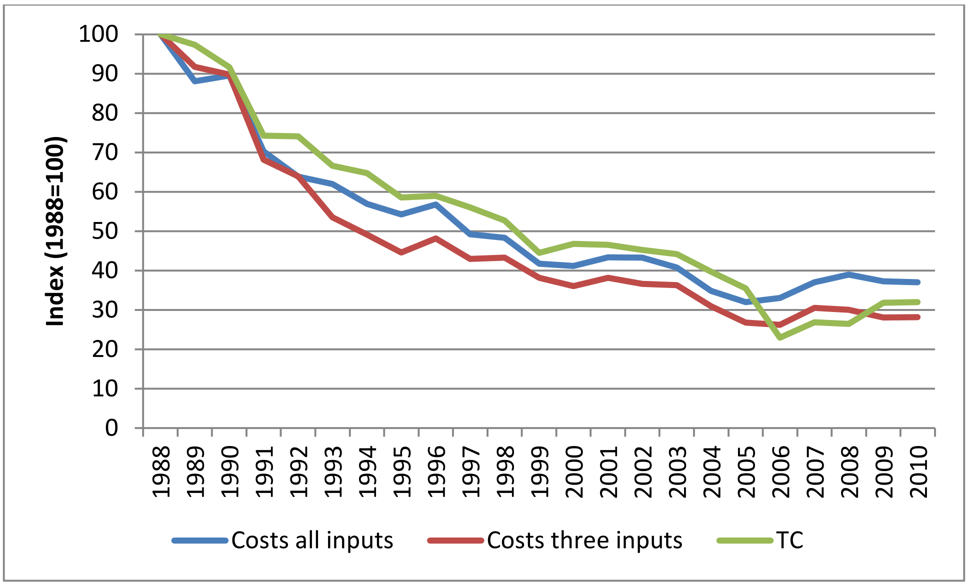
Table 3. Estimated rates of technical change evaluated at sample mean values for cost model estimated by Seemingly Unrelated Regression.

Elasticity	Estimate	Standard error	t-value	P-value
TC_{pure}	-0.2060	0.046	-4.45	0.000
TC_{factor}	0.0204	0.019	1.26	0.207
TC_{scale}	0.1410	0.044	3.20	0.001
TC	-0.0415	0.004	-10.06	0.000

$TC = TC_{pure} + TC_{factor} + TC_{scale}$

However, the rate of technical progress predicted by our model is not even over time. If we examine the development of the rate of technical progress over time, we find a significant stagnation for the last data years. During the five-year period 1991-1995 the average predicted rate of technical progress was 8.3 % and during 1995-2000 it was 4.1%. For the years 2001-2005 it was 5.3%, but only 0.2 % for the final period 2006-2010. Estimated rates of the technical progress by year are shown in Figure 3 as the green line (TC).

Figure 3. Production costs and technical change index.



In addition, the figure illustrates both the production costs of all inputs in the period from 1988 to 2010 (blue line), and the production costs only for the three inputs (red line) used in the regression model (feed, labor and capital). Figure 3 provide evidence that a substantial technological progress has taken place in juvenile production during the period 1988-2010, and this progress has to a large extent followed the development of the costs.

9 CONCLUSIONS

This study examines productivity development for Norwegian juvenile salmon producers, and provides information on this sector's contribution to the Norwegian salmon aquaculture industry's productivity and competitiveness development. High productivity in all stages of the value chain for salmon determines the competitiveness of the industry, and productivity growth for the suppliers reduce costs in grow-out farms.

The production process in juvenile production in the Norwegian salmon industry has changed substantially due to innovations in key technologies as breeding, fish feed, equipment, fish health and water technology. The production has become closed or semi-closed with a large degree of control in the different processes. Many of the operational tasks in land-based production of smolt has been streamlined and automated (Asche & Bjørndal, 2011) and we found this has contributed to significantly increasing productivity in the industry since the late 1980`s.

The juvenile salmon producers' production costs have declined substantially over time since the late 1980s. This comes in addition to the quality improvement that has increased survival rates and reduced disease outbreak after released to the sea. One of the most important factors explaining the reduction in production costs is increasing scale for the farms. The number of farms has been reduced while the production at each farm has increased. The fact that juvenile salmon producers operate at increasing returns to scale is probably explained by the government restriction on farm level output, and implies that relaxation of the restriction will lead to lower production costs.

Unit production costs in Norwegian salmon hatcheries have been stagnant in recent years, and even increased slightly. Our econometric analysis has allowed us to identify the role of technical change for cost reduction. We find that the industry has experienced an annual average rate of technical progress of 4.1 % over the period 1988-2010. However, the rate of technical progress has slowed down the recent years. For the years 2006 -2010 the technical progress has been < 1%, suggesting that the industry is struggling to innovate at a rate that can provide lower production costs.

A substantial part of the cost savings due to productivity increase in juvenile production is passed on to the grow-out farms in the form of lower prices, as this makes Norwegian salmon aquaculture products more competitive relative to other food producers. Hence, it is crucial that different stages of the salmon aquaculture value chain, including the juvenile production stage, increase their productivity. The results from this study suggest that the juvenile salmon stage has not been able to contribute to productivity growth at the same rate as earlier. This has been manifested in stagnant and even increasing juvenile salmon production costs and smolt prices from these producers in recent years.

ACKNOWLEDGEMENTS

The authors would like to thank two reviewers for helpful comments and to acknowledge financial support from the Norwegian Research Council. Any remaining mistakes are the authors’ responsibility.

APPENDIX

Translog Cost Function Parameter Estimates:

Equation	Observations	Parameters	Root-Mean- Square Deviation	R-squared
Cost function	1802	130	0.368	0.999
Feed share eq.	1802	28	0.098	0.893
Labor share eq.	1802	28	0.109	0.945

Variable	Coefficients	Stdandard Error	t-value	p-value
α_0	-0.408	1.620	-0.250	0.801
α_F	0.448	0.064	7.050	0.000
α_K	0.618	0.532	1.160	0.245
α_L	1.151	0.069	16.590	0.000
α_{LL}	0.022	0.005	4.770	0.000
α_{FL}	-0.040	0.007	-5.850	0.000
α_{KL}	0.000	0.009	0.010	0.989
α_{FF}	-0.015	0.006	-2.500	0.013
α_{FK}	0.009	0.008	1.240	0.216
α_{KK}	-0.013	0.037	-0.350	0.726
α_y	0.834	0.219	3.800	0.000
α_{yy}	-0.010	0.008	-1.240	0.214
α_{yL}	-0.039	0.004	-10.830	0.000
α_{yF}	0.011	0.003	3.420	0.001
α_{yK}	-0.081	0.035	-2.290	0.022
α_{FRY}	-0.372	0.331	-1.120	0.261
$\alpha_{FRY\,y}$	-0.019	0.023	-0.810	0.419
$\alpha_{FRY\,F}$	0.004	0.006	0.740	0.458
$\alpha_{FRY\,K}$	-0.084	0.051	-1.670	0.096
$\alpha_{FRY\,L}$	0.030	0.007	4.620	0.000

α_{1989}	-1.418	1.074	-1.320	0.187
α_{1990}	0.794	0.957	0.830	0.407
α_{1991}	-1.363	1.022	-1.330	0.182
α_{1992}	-2.436	0.893	-2.730	0.006
α_{1993}	-2.295	0.998	-2.300	0.021
α_{1994}	-3.850	0.957	-4.020	0.000
α_{1995}	-3.010	0.929	-3.240	0.001
α_{1996}	-2.793	0.845	-3.300	0.001
α_{1997}	-3.249	0.905	-3.590	0.000
α_{1998}	-4.032	1.000	-4.030	0.000
α_{1999}	-2.954	0.946	-3.120	0.002
α_{2000}	-3.736	1.006	-3.710	0.000
α_{2001}	-3.694	1.000	-3.690	0.000
α_{2002}	-6.137	0.986	-6.220	0.000
α_{2003}	-4.222	1.006	-4.200	0.000
α_{2004}	-4.947	1.093	-4.530	0.000
α_{2005}	-5.329	1.098	-4.850	0.000
α_{2006}	-4.734	1.071	-4.420	0.000
α_{2007}	-5.329	1.012	-5.270	0.000
α_{2008}	-5.208	1.034	-5.030	0.000
α_{2009}	-4.359	1.100	-3.960	0.000
α_{2010}	-5.390	1.047	-5.150	0.000
$\alpha_{y\,1989}$	0.100	0.071	1.410	0.159
$\alpha_{y\,1990}$	0.000	0.063	0.000	0.997
$\alpha_{y\,1991}$	0.158	0.073	2.160	0.031
$\alpha_{y\,1992}$	0.199	0.059	3.350	0.001
$\alpha_{y\,1993}$	0.190	0.068	2.800	0.005
$\alpha_{y\,1994}$	0.271	0.063	4.320	0.000
$\alpha_{y\,1995}$	0.183	0.061	3.020	0.003
$\alpha_{y\,1996}$	0.212	0.058	3.690	0.000
$\alpha_{y\,1997}$	0.196	0.061	3.200	0.001
$\alpha_{y\,1998}$	0.240	0.070	3.440	0.001
$\alpha_{y\,1999}$	0.090	0.065	1.400	0.163
$\alpha_{y\,2000}$	0.199	0.071	2.810	0.005
$\alpha_{y\,2001}$	0.202	0.063	3.200	0.001
$\alpha_{y\,2002}$	0.401	0.066	6.060	0.000
$\alpha_{y\,2003}$	0.206	0.063	3.280	0.001

$\alpha_{y\ 2004}$	0.242	0.070	3.450	0.001
$\alpha_{y\ 2005}$	0.278	0.072	3.880	0.000
$\alpha_{y\ 2006}$	0.209	0.071	2.940	0.003
$\alpha_{y\ 2007}$	0.271	0.066	4.120	0.000
$\alpha_{y\ 2008}$	0.270	0.067	4.000	0.000
$\alpha_{y\ 2009}$	0.227	0.076	2.990	0.003
$\alpha_{y\ 2010}$	0.300	0.072	4.180	0.000
$\alpha_{F\ 1989}$	0.009	0.017	0.530	0.596
$\alpha_{F\ 1990}$	0.009	0.017	0.540	0.589
$\alpha_{F\ 1991}$	0.006	0.018	0.360	0.715
$\alpha_{F\ 1992}$	0.059	0.017	3.520	0.000
$\alpha_{F\ 1993}$	0.027	0.016	1.670	0.096
$\alpha_{F\ 1994}$	0.045	0.016	2.830	0.005
$\alpha_{F\ 1995}$	0.060	0.016	3.840	0.000
$\alpha_{F\ 1996}$	0.042	0.015	2.770	0.006
$\alpha_{F\ 1997}$	0.053	0.016	3.350	0.001
$\alpha_{F\ 1998}$	0.073	0.016	4.460	0.000
$\alpha_{F\ 1999}$	0.084	0.016	5.110	0.000
$\alpha_{F\ 2000}$	0.036	0.017	2.180	0.029
$\alpha_{F\ 2001}$	0.024	0.017	1.420	0.155
$\alpha_{F\ 2002}$	0.027	0.017	1.600	0.109
$\alpha_{F\ 2003}$	0.034	0.017	2.000	0.045
$\alpha_{F\ 2004}$	0.026	0.018	1.450	0.147
$\alpha_{F\ 2005}$	0.021	0.018	1.170	0.242
$\alpha_{F\ 2006}$	0.073	0.018	4.040	0.000
$\alpha_{F\ 2007}$	0.036	0.017	2.100	0.036
$\alpha_{F\ 2008}$	0.028	0.017	1.620	0.105
$\alpha_{F\ 2009}$	0.035	0.018	1.970	0.049
$\alpha_{F\ 2010}$	0.040	0.018	2.280	0.023
$\alpha_{K\ 1989}$	-0.136	0.421	-0.320	0.747
$\alpha_{K\ 1990}$	0.476	0.378	1.260	0.209
$\alpha_{K\ 1991}$	0.671	0.334	2.010	0.044
$\alpha_{K\ 1992}$	0.550	0.319	1.730	0.084
$\alpha_{K\ 1993}$	0.597	0.323	1.850	0.064
$\alpha_{K\ 1994}$	0.428	0.316	1.350	0.176
$\alpha_{K\ 1995}$	0.411	0.313	1.310	0.189
$\alpha_{K\ 1996}$	0.660	0.321	2.060	0.040

$\alpha_{K\ 1997}$	0.314	0.328	0.960	0.339
$\alpha_{K\ 1998}$	0.322	0.343	0.940	0.347
$\alpha_{K\ 1999}$	-0.151	0.346	-0.440	0.662
$\alpha_{K\ 2000}$	0.045	0.349	0.130	0.898
$\alpha_{K\ 2001}$	0.009	0.354	0.030	0.979
$\alpha_{K\ 2002}$	0.264	0.350	0.760	0.450
$\alpha_{K\ 2003}$	-0.249	0.364	-0.680	0.495
$\alpha_{K\ 2004}$	-0.347	0.361	-0.960	0.337
$\alpha_{K\ 2005}$	-0.123	0.348	-0.350	0.724
$\alpha_{K\ 2006}$	0.270	0.310	0.870	0.385
$\alpha_{K\ 2007}$	-0.023	0.329	-0.070	0.945
$\alpha_{K\ 2008}$	0.048	0.316	0.150	0.880
$\alpha_{K\ 2009}$	0.363	0.306	1.190	0.236
$\alpha_{K\ 2010}$	0.441	0.302	1.460	0.144
$\alpha_{L\ 1989}$	-0.030	0.019	-1.540	0.124
$\alpha_{L\ 1990}$	-0.059	0.019	-3.020	0.003
$\alpha_{L\ 1991}$	-0.003	0.020	-0.170	0.864
$\alpha_{L\ 1992}$	-0.017	0.019	-0.910	0.364
$\alpha_{L\ 1993}$	0.025	0.019	1.350	0.178
$\alpha_{L\ 1994}$	0.033	0.018	1.810	0.070
$\alpha_{L\ 1995}$	0.045	0.018	2.500	0.012
$\alpha_{L\ 1996}$	0.026	0.018	1.470	0.143
$\alpha_{L\ 1997}$	0.031	0.018	1.710	0.086
$\alpha_{L\ 1998}$	0.028	0.019	1.490	0.136
$\alpha_{L\ 1999}$	0.033	0.019	1.740	0.082
$\alpha_{L\ 2000}$	0.039	0.019	2.040	0.042
$\alpha_{L\ 2001}$	0.031	0.019	1.610	0.108
$\alpha_{L\ 2002}$	0.038	0.020	1.920	0.054
$\alpha_{L\ 2003}$	0.022	0.020	1.120	0.264
$\alpha_{L\ 2004}$	0.029	0.020	1.450	0.147
$\alpha_{L\ 2005}$	0.058	0.020	2.860	0.004
$\alpha_{L\ 2006}$	0.133	0.021	6.330	0.000
$\alpha_{L\ 2007}$	0.082	0.020	4.130	0.000
$\alpha_{L\ 2008}$	0.094	0.020	4.730	0.000
$\alpha_{L\ 2009}$	0.128	0.021	6.170	0.000
$\alpha_{L\ 2010}$	0.130	0.020	6.410	0.000

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Paper II

Paper III

Paper IV