

**THE DEVELOPMENT OF LARGE-SCALE AQUACULTURE
PRODUCTION:
A COMPARISON OF THE SUPPLY
CHAINS FOR CHICKEN AND SALMON**

Frank Asche^{a,b,*}, Andreea L. Cojocaru^b, Bjørn Roth^c

Affiliations:

- a. Institute for Sustainable Food Systems and School of Forest Resources and Conservation, University of Florida, Gainesville, FL 32611-0180, USA
- b. Department of Industrial Economics, University of Stavanger, Stavanger 4036, Norway
- c. Nofima AS, Stavanger 4021, Norway

* Author for correspondence, e-mail: frank.asche@ufl.edu

Abstract: The supply chain for salmon is, in many respects, the world's most efficient seafood supply chain. Adopting new technologies and expanding the scale of production have improved competitiveness leading to increased production and industry growth. The transfer of knowledge and processes from other food producing industries has facilitated growth in salmon aquaculture in particular, and in aquaculture in general. As such, the maturity of the salmon industry relative to other food producing industries can provide indications of further growth potential. We argue that the salmon industry still has much to learn from similar processes in other food-growing industries. Notably, the production and processing of poultry has experienced significant increases since the 1940s, becoming the fastest growing and most rapidly changing highly intensive livestock farming segment, with often fully-automated processing environments. Although farmed salmon has a production history closely following that of poultry, it remains semi-automated with less control over production processes and a more limited product specter than poultry. While this gives important avenues of growth for salmon, it holds even more potential for other aquaculture species with even less control over the production processes and supply chain.

Keywords: aquaculture, salmon, chicken, production process, supply chain, market

1. INTRODUCTION

Aquaculture has been the world's fastest-growing food production technology during the last three decades, with an annual average growth rate of 6.2% since 2000 (FAO, 2014). As more aquatic species are becoming domesticated, the production practices in aquaculture, particularly for fed species, are becoming increasingly comparable to those of agricultural meat production based on grain and oilseeds (Forster and Hardy, 2001; Torrissen et al., 2011). Still, aquaculture is in many ways a new industry, as systematic R&D did not commence on any significant scale until the 1970s (Asche, 2008; Kumar and Engle, 2016), and large-scale market impact did not occur until the 1990s (Asche et al., 2015).

Salmon is one of the leading species in modern aquaculture in terms of control within the production process, sophistication of supply chains and product spectrum (Anderson, 2002; Asche, 2008; Kumar and Engle, 2016). The global production of farmed salmon exceeded 3.4 million metric tons (mt) in 2014 (FAO).¹ Although that quantity only represents 4.7% of the total aquaculture production volume, it accounts for over 12.9% of the production value, making salmon the second most valuable farmed species after shrimp.²

It is well established that the success of aquaculture in terms of increased production is achieved through innovation, productivity improvements, and cost reduction at all levels in the supply chain, from the production stage to the market. An important part of this process has been the transfer or adoption of technologies and knowledge from the agricultural sciences (Anderson, 2002; Asche, 2008; Kumar and Engle, 2016). This suggests that the development of successful species in terrestrial animal production may contain a number of useful insights with respect to the future development of aquaculture. In this paper, the objective is to gain some of these insights by comparing the progress of salmon, the most advanced aquaculture species in production as well as marketing (Kumar and Engle, 2016), to chicken, one of the fastest growing and most efficient terrestrial meat species (FAO, 2010).

¹ Atlantic salmon is the most commonly farmed of the salmonide, and its share of the production has been increasing. Substantial quantities are produced also of coho and rainbow trout, while much more limited quantities are produced of other species like chinook.

² Shrimp production in 2014 represented approximately 6.3% and 15% of total aquaculture quantity and value, respectively. (Source: FAO, accessed May 12, 2016)

The quantity of chicken produced in 2011 was 3.5 times that of 1970, and the global production in 2011 surpassed 95 million mt, according to the FAO database. Over a span of fewer than 6 decades, the chicken industry has evolved from fragmented, locally owned businesses into one of the most efficient, vertically integrated parts of agriculture production. The obvious question to ask when interested in the potential for future growth in aquaculture species such as salmon, is what aspects of the production process contributed to this success, what are the similarities in the development of salmon aquaculture relative to chicken and how much knowledge is there still to transfer.

We will first provide a description of the development of the modern chicken industry focusing on changes in the production process, as well as supply chain and product forms. This will be followed by a description of the same process for salmon and finally, a comparison of the two industries. While the focus of the article is on salmon, as a leading species in modern aquaculture, the insights from improved production technologies, through the supply chain and to the market, are relevant for most aquaculture species. The data used for the comparison come mainly from the USA, historically the largest and most technologically advanced broiler producer, and from Norway, the main producer of farmed Atlantic salmon. However, we know that some and believe that most of the remaining insights are representative for producers in all countries using modern production processes.

2. THE CHICKEN INDUSTRY

In the early 1900s, chicken was not considered part of the animal breeding industry (Pearl, 1916), and the quantity produced was limited. Chicken production was characterized by small flocks of birds raised on individual farms for family consumption of eggs and meat, and possibly limited sales at local markets. A first step towards industrialization came with the introduction of commercial feed mixtures in the 1910s to replace the more time consuming and less controlled conventional free grazing (Heuser, 2003). This was first aimed at improving egg-laying rates, but it marked the emergence of the first specialized producers in the supply chain for chicken.

As the demand for and production of eggs went up in the early 20th century, farmers were faced with an excess amount of young male birds, making increasing quantities of meat available. Their sale gave rise to the market for poultry meat. With increased poultry consumption, it became evident that some birds were better for laying eggs, while others were better for meat production. In America, in the 1920s and 1930s, instead of the dual-purpose chickens (raised for both eggs and meat), farmers began to raise single purpose chickens, used for either eggs or meat production and sold them at local farmers' markets. Raising birds for meat was done year-round and the demand for chicken products experienced an increase. The modern broiler industry started to develop in the northeastern USA, but production gradually moved south due to abundant cheap land, labor, and more advantageous climate (Gardner, 2002).

Primary processing of birds was typically performed by hand. Growth in production had the immediate implications that the process required more labor. Therefore, speedier and more tailored delivery of the final product was the natural step to take. Specialized harvesting was introduced in 1942 when the first plant set up to perform evisceration on a line gained its government approval. This was followed by automated ways to kill and process the birds, and specialized processors began to sell slaughtered and cleaned birds. At the time, the most popular option was the “New York Dressed”, a readily plucked chicken carcass with feet and head intact (Shamshak and Anderson, 2008). While initially the hung birds were stationary and workers had to move between processing stations, the practice drifted towards stationary workers and eventually robotic arms, with birds moving on conveyor belts. The whole chicken carcass was moved through automated machinery where it was cut up into parts, and/or deboned (Barbut, 2010). These more capital intensive production processes also increased the scale of the plants.

An important turning point for the industrialization of chicken production for meat came in 1945 when the Great Atlantic & Pacific Tea Company (A&P), the largest poultry retailer at the time, held a national contest in partnership with the United States Department for Agriculture (USDA) for the “Chicken of Tomorrow”.³ The

³ United States has consistently been the largest broiler producer since 1960, with an average share of nearly 25% (Source: National Chicken Council, accessed June 29, 2015).

contest entailed producing a breed of chicken that would grow faster and bigger than commercial chickens at the time. Eventually, this challenge resulted in the creation of the Arbor Acre breed that came to dominate the genetic stock of chicken worldwide and is being produced and consumed to this day (Wiehoff, 2013). The combination of new breeds, targeted feed and a controlled environment made today's broilers slaughter-ready in 6-8 weeks, compared to 16-17 weeks in the 1920s (Figure 1).⁴

Genetic improvement as a technological development, aims to save on the input of production factors by setting up a new production function (Cochrane, 1958; Groen, 2003). Line specialization and crossbreeding were gradually introduced, in support of this. The breeding program started with increased live weight as the main goal and progressively added additional traits such as improved feed conversion, immune response, meat quality, and breast meat. Accumulated knowledge resulted in a number of specialized lines in broiler breeding, each with distinct goals. This allowed breeders to adapt their type of meat chickens to changes in production and consumption trends. Final product broilers today are the result of three- or four-way crossings between specific lines of purebred chickens (Arthur and Albers, 2003).⁵

Genetics alone are not sufficient to ensure increased productivity, and feed specialization contributed dramatically to changing growth rates. This is reflected in the developments in feed conversion ratios, which is a measure of how well broilers convert feed into weight. If in the beginning of the 20th century farmers used over 4kg of feed to create 1kg of meat, currently less than half of that amount is necessary to achieve the same goal (Figure 1), given a suitable environment for rapid bird development.

⁴ The average slaughter age for a broiler in the United States is 47 days at a weight of 2.6kg (National Chicken Council, 2015).

⁵ Arthur and Albers (2003) provide an overview of the evolution in breeding programs and breeding techniques, as well as a description of the breeding goals over time.

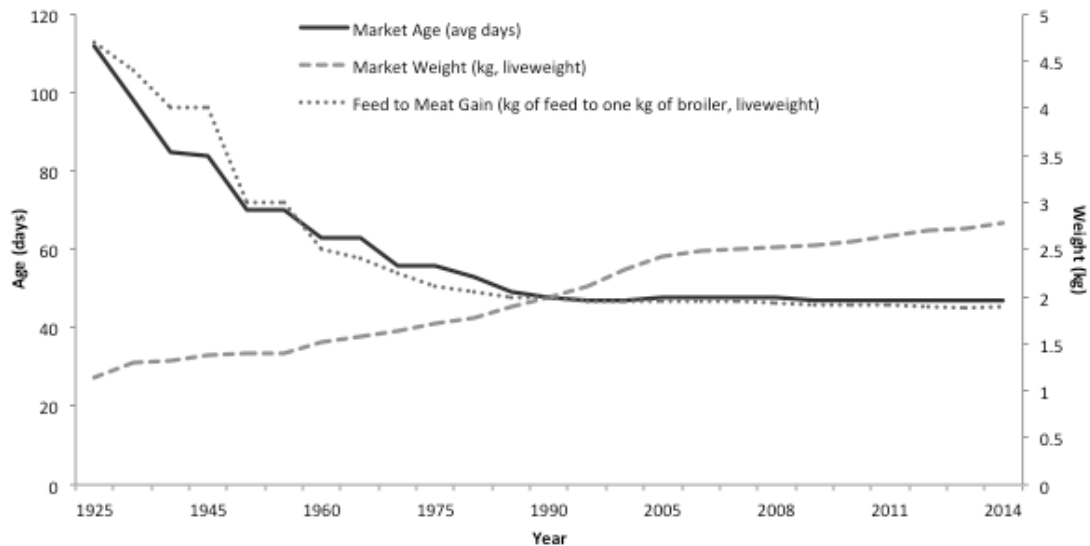


Figure 1: Market age and weight changes, and feed-to-meat gain.

Source: National Chicken Council (accessed June 29, 2015)

Newly hatched chicks require ambient temperatures of 32 to 35 degrees Celsius, with humidity rates between 50% and 70%, adequate lighting and a disease-free environment for optimal growth. Technological research allowed the industry to gain and maintain a high degree of control over the light, temperature and ventilation in the broiler houses, improving growth conditions. Farms were able to opt for higher capacity, and moved from raising 500 birds in the 1920s to three or four broiler houses per modern farm, each holding 70,000 birds (Barkley and Barkley, 2015). Additionally, disease eradication programs, such as The National Poultry Improvement Plan (NPIP), have been implemented in support of large-scale production to minimize or avoid the infection and/or spread of diseases at farm level (Marangoni and Busani, 2006).⁶

Specialization on multiple levels of the industry was key in lowering costs for the producers. Between 1915 and 1940, feed (mainly corn and soybean meal) accounted for 50-70% of chicken production cost, followed by newly hatched chicks and labor costs. The broiler-feed price ratio, a simple ratio of live broiler market price per kilogram to grower feed price (derived from corn and soybean prices) per kilogram, is considered to be a useful guide for costs in broiler production (Fisher, 1958). Figure 2

⁶ The NPIP is a co-operative Federal-State-Industry program established in the United States in 1935.

provides an indication of how many units of feed could be purchased with one unit of sold product over time. The overall trend appears to indicate that production increased in profitability throughout the years. The lower production cost also made US chickens competitive in export markets (Walker, 1964), and contributed to the development of similar industries in other developed countries.

The early stages of the industrialization of the chicken industry were characterized by increased specialization (e.g. hatcheries, feed, farms, processing plants) and the exploitation of economies of scale. However, increasingly, the focus was on better coordination and by the mid-1960s, 90% of the broiler industry had transitioned from specialized producers to a vertically integrated business, taking part in every stage of production, processing and marketing. In the 1970s, the poultry industry moved toward the efficient, less-waste producing processes, by means of automation and use of all parts of the bird. To cite Barbut (2010, pp. 399), “these advancements have been possible by gaining knowledge in areas such as computer science (e.g. image analysis, on line weighing and tracking), live bird handling (transportation, unloading, stunning), muscle biology (post mortem processes), heat and mass transfer (scalding, chilling), and engineering (machine building, metallurgy).” Due to these innovations, by 2009, the processing speed of a line had quadrupled, compared to the 1970s when only 3,000 broilers were being processed each hour (Table 1).



Figure 2: Average broiler feed-price ratio in the United States.

Source: USDA National Agricultural Statistics Service (accessed March 16, 2016)

Table 1: Broiler processing line speed over time, and major equipment developments, *table from* (Barbut, 2010)

Year	Line speed (broilers/h)	Major developments
1970	3,000	
1975	4,500	Evisceration
1980	8,000	
1990	9,000	Giblet harvest
2000	10,500	Cut-up
2009	12,000	Automated Controlled Atmosphere Stunning



Figure 3: Real US broiler retail and wholesale prices, and quantity produced. *Source: National Chicken Council and FAO (accessed March 17, 2016)*

The increases in productivity of the chicken industry in combination with the increase in quantity produced have, over time, been reflected in lower retail prices (Figure 3). Noteworthy is that the retail price has declined more than the wholesale price, indicating productivity growth also at the end of the supply chain. This increased competitiveness has in turn influenced consumers to substitute away from other meats

(Fulginiti, 1996). In addition, as the developed world was seeing more and more women entering into the workforce in the 1980s, convenient, ready to cook food products started to gain market share. Figure 4 shows how the chicken meat production evolved over time from meat sold mainly as whole chicken to include the increased demand in a variety of cuts and value-added products.

Hence, to meet the consumer’s ever changing needs, the demand from the producer’s side for filleting and deboning machinery also increased (Barbut, 2010). Perhaps the most significant example of automation when it comes to filleting is associated with the introduction of the chicken finger or the chicken nugget in 1979, which required a particular boneless cut. Although the initial cut was done manually, it was later accomplished faster and more economically on the line (Barbut, 2010). Furthermore, through these technological advancements, the chicken processors increased the value of the bird by using more of it: blood is collected and used in composting, the bones are used to make bone meal, which along with other trimmings is used to make animal feed or plant fertilizer; what is removed after slaughter is also sold separately or is further processed into by-products.

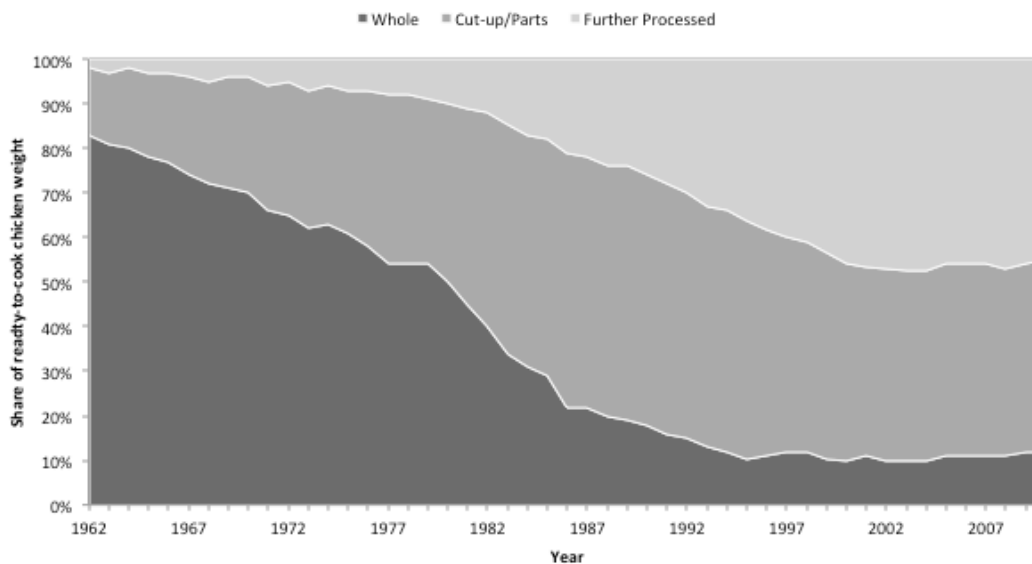


Figure 4: US Broiler processing percentages.

Source: National Chicken Council and FAO (accessed June 29, 2015)

The development of value-added products also provided more choice for the consumer. Higher quality cuts and a larger product range in combination with reduced waste contributed to increased profitability. In the early 1960s, whole chickens accounted for more than 80% of the birds sold to consumers, while in recent years, with more than 3,000 different chicken products available in grocery stores, whole birds account for 5-10% of sales. This does not mean that production of whole birds has dramatically decreased over time. Figure 5 shows that whole chicken production has not experienced great fluctuations, but that chicken production has increased to meet the demand for a wider variety of product forms. The increase in processed chicken products is a strong indicator that this side of the industry has been thriving, and that new product forms are contributing to a growing demand, as chicken becomes the basis for more versatile product settings.

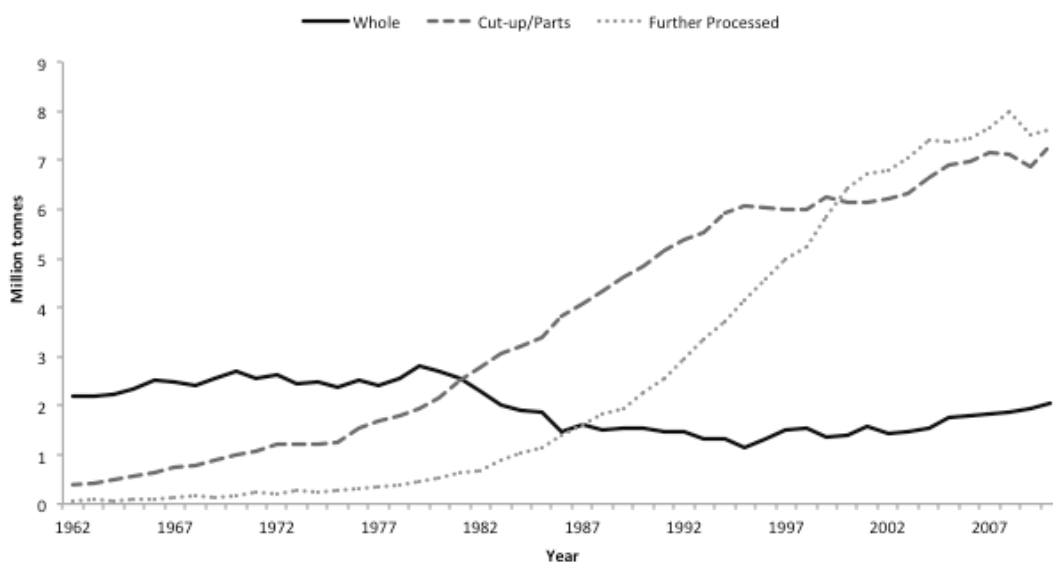


Figure 5: US Chicken production by product form. *Source:* National Chicken Council and FAO (accessed June 29, 2015)

3. THE SALMON INDUSTRY

Prior to the 1970s, salmon was supplied with large seasonal variations to high-end markets as a luxury product, and was primarily wild caught. This market opportunity started to be exploited at a larger scale in 1969 due to the invention of the net pen, a device that allowed a part of the water column to be fenced in (Gjedrem et al., 1991).

Salmon is an anadromous species, where the eggs are hatched in fresh water, and the young salmon in the wild spend several years in fresh water before adapting to the marine environment. This transition period is known as “smoltification”. Salmon farmers have been successful in mimicking the salmon’s natural cycle, and the production consists of three main stages: egg production, smolt production and the grow-out operation. For the majority of the salmon industry the flesh is the main product. However, “egg producers” also exist for salmon. In particular, roe is the Danish salmon aquaculture industry’s main product. Initially, salmon farmers benefited greatly from efforts to enhance wild fish stocks via hatcheries because the production in the early life stages was already mastered due to these efforts (Nielsen et al., 2016). This provided control over the entire production cycle from the early days of salmon aquaculture, and allowed systematic R&D efforts throughout the supply chain from the start.

The R&D and resulting innovations led to a substantial productivity growth that has reduced real production cost by more than two thirds, as shown in Figure 6. As one would expect in a competitive industry, these gains are passed on to the consumers in terms of lower prices, while the industry benefits from the increased competitiveness of its product through a higher quantity produced and higher market share (Asche, 2008). There is a large literature investigating the productivity growth in salmon aquaculture and documenting how this has reduced production cost (Asche et al., 2013a). We will here discuss some of the most important elements in more detail as the new technology has increased scale as well as shifted the input mix.

One of the first and most important R&D efforts was a 4-year systematic breeding program established by AKVAFORSK in 1973 (Gjedrem, 2000). The program’s primary goal was to increase productivity by creating fish with superior growth rates and growth times compared to their wild equivalents. Eventually, this challenge resulted in the creation of a genetically improved breed of salmon with a growth rate of even up to 77% faster than in the wild (Gjedrem, 2000; Gjerde et al., 1997). In the 1980s, the production time from hatching to smolt lasted generally 2 to 3 years, while contemporary production is done within the same year or by spring of the following year (Sandvold and Tveteras, 2014).

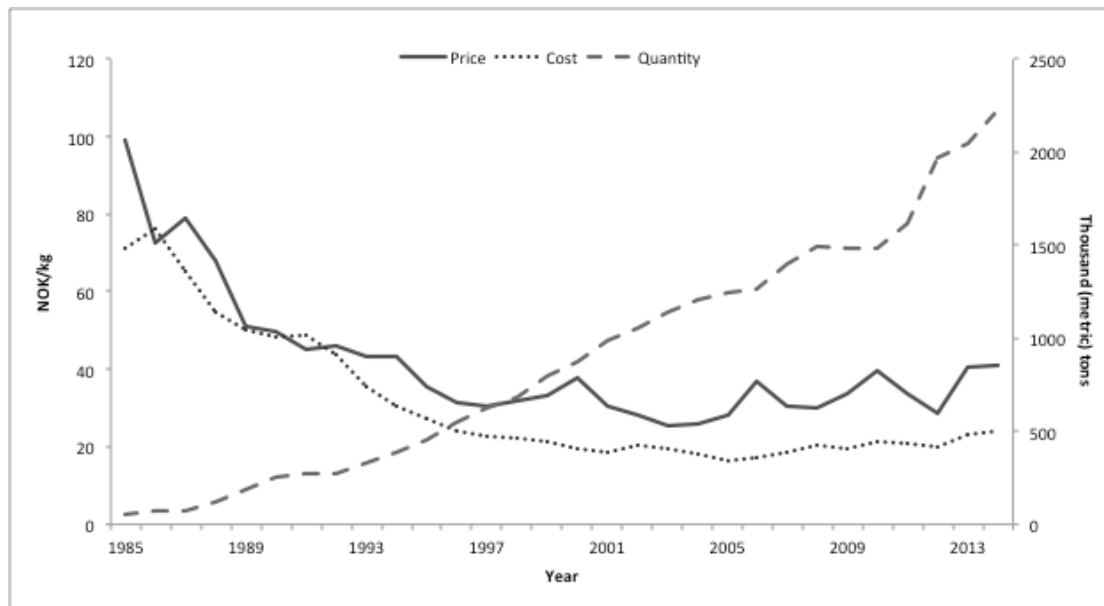


Figure 6: Real Norwegian salmon price and production cost, and global production.

Source: FAO and Directorate of Fisheries

The feed conversion ratio for salmon aquaculture has decreased over time (Tveterås, 2002). In the 1980s, one kilogram of farmed salmon required more than three kilograms of feed, while today, in combination with the more targeted feed composition, the most experienced farmers are able to produce one kilogram of fish with just over one kilogram of feed (Guttormsen, 2002; Knapp, 2007; Tacon and Metian, 2008). The composition of the feed itself has gone from in-house mixes of lower-quality marine fish catches and other waste from food processing plants, to highly knowledge-based feeds produced by specialized companies.⁷ An initial tipping point came in 1982, when the dry pellet feed was introduced (Asche and Bjørndal, 2011). Salmon farming remained however highly dependent on the qualities of the marine ingredients used in the feed due to them being a basis for the salmon’s flesh pigmentation as well as a source of Omega-3 oils. From the late 1990s, improved nutritional knowledge has allowed a higher percentage of vegetable-based ingredients

⁷ Low-quality fish catches or landings refer to wild caught fish that is of low-value, typically used in the production of fishmeal and fish oil.

to be used in the dry-pellet feed, reducing the dependence on marine ingredients and improving control on costs (Kristofersson and Anderson, 2006; Tacon and Metian, 2008; Ytrestøyl et al., 2015; Asche and Oglend, 2016).

The grow-out of the fish takes place in sea pens, a practice that has not changed since 1969. Technological innovation has, on the other hand, allowed farmers to produce smolts in closed, land-based highly controlled environments instead of open-pond systems (Sandvold and Tveteras, 2014; Sandvold, 2016), and there is substantial research interest in land-based facilities also for the grow-out phase. Over time, improvements in pens, increased pen sizes and automatic feeders enabled the scale of each plant to increase substantially from producing less than 100 mt of fish a year to producing over 5000 mt a year. In 1980 a Norwegian salmon sea pen measured 5m in diameter and 4m in depth, while in 2013 its measurements were 70m and 45m, respectively (Asche et al., 2013b). This has also led to better capacity utilization. Guttormsen (2002) noted that between 1986 and 1998, despite the significant reduction in the real price of feed, the relative feed cost share went from 27% to 50%. An increasing feed cost share is a signal that all remaining cost-contributing factors are becoming more efficient. Currently, the cost share of feed exceeds 55% (Fiskeridirektoratet, 2015).

In the 1980s, disease created substantial challenges for the salmon industry. At first, the only available tool to keep bacteria under control was the use of antibiotics, administered through medicated baths or feed. However, as veterinary knowledge expanded, antibiotic use was reduced to almost zero (Tveterås, 2002). Also with respect to other diseases there have been improvements, as a superior management system has moved the focus towards preventative vaccination rather than treatment (Torrissen et al., 2011). Still, diseases and parasites continue to pose challenges. For example, an outbreak of infectious salmon anemia resulted in the Atlantic salmon production declining by two thirds in Chile in 2009 (Torrissen et al., 2013). Salmon lice is however seen as the most serious problem that the salmon industry is facing at the moment (Torrissen et al., 2013) and research is actively conducted to find ways of containing and eradicating this parasite.

By the 1980s, production had increased enough to allow for investments in small, specialized slaughtering facilities mostly farm-related, where the fish were gutted, bled and filleted, also by hand. In the 1990s, the salmon industry began moving toward a less-wasteful production process by making use of specialized harvesting systems, and also utilizing the trimmings and cut-offs.⁸ Even though the first automated cleaning and cutting machine, known as the “Iron Butcher”, was developed as early as 1903 by inventor Edmund A. Smith, it was not until the later part of the 20th century that an array of processing technologies became available to the salmon industry, mainly as knowledge transfer from white fish. The salmon industry today has access to advanced equipment and systems for all stages within its value-chain, from gutting and weighing, to filleting, skinning, deboning and portioning. Large processing plants have also facilitated the move from labor-intensive production to more capital-intensive production. Within the larger processing plants, a production line can handle close to 6,500 fish per hour. Despite these advancements, the processing speed is negatively affected by a number of manual interventions that continue to be necessary, as well as by steps that are time-consuming and involve the use of large refrigerated saltwater tanks for maintaining a low temperature inside the fish.

Transportation over long distances was facilitated by the application of leak-proof polystyrene foam packaging, which gradually created a global market. Opportunities for market expansion, together with packaging innovation, made transportation means attractive, and airfreight more so when the USA and Asia became significant markets in the mid-1980s (Asche and Bjørndal, 2011). For example, Asche and Bjørndal (2011) note that the transportation cost per kilogram of frozen salmon from Chile to any part of the world is around 0.50USD. This endeavor came to prove that producers, regardless of location, could access the market and distribute a variety of products. Air transport costs are influenced by the distance between the exporter and the destination market, but other factors such as return freight can be equally important.

⁸ Associated with this development was the well-boat industry, the seagoing equivalent of a truck, for live transport.

The lowering of production costs and price (Figure 6) enabled salmon to become competitive in new market segments first geographically, as the market became global, and increasingly thereafter through product development. The industry has since been producing a number of different processed product forms, with smoked salmon being the most notable given its gain in market share. However, the development of value-added products is still limited. Figure 7 shows the product shares in France, the most developed salmon market in the EU in 2013.

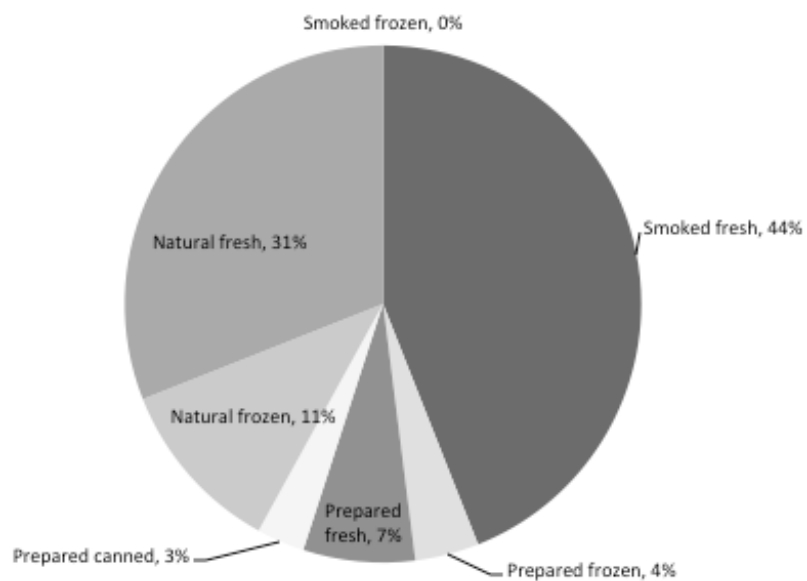


Figure 7: Salmon consumption by product form in France in 2013.

Source: Europanel

Natural fresh and frozen, and smoked salmon altogether account for more than 85% of product shares when considering France’s total consumption. The increased degree of handling the products has also led to the creation of high-value cuts like loins, similar to the chicken fillets, as well as some products based on nuggets, trimmings and cut-offs. The developments in this respect have been limited and whole and filleted salmon, whether fresh, frozen or smoked, remain the main final products. Only recently has one been able to create markets for waste resulting from salmon processing. For example, a market was created for fish heads after the turn of the century. In Norway, of the live fish weight going into filleting, approximately 35%

represent trimmings and offal. Much of this quantity is reduced into fish oil and fishmeal, or into silage.

Over time, salmon aquaculture has been moving away from the organization model found in traditional fisheries. Small companies that used to operate in one location have evolved into large companies operating on multiple locations and supported by other sectors. During the last decade the industry has begun on its path to integrate vertically, as well as horizontally, by creating large companies that own both farms and processing operations. As the processing operations have increased in scale, their number has declined (Asche et al., 2013b; Kvaløy and Tveteras, 2008; Olson and Criddle, 2008).

4. COMPARISON

While the salmon industry has come a long way since its beginnings in the 1970s, there is tremendous potential for further development when compared with chicken. In this section, important similarities and differences will be highlighted. This will show that there are many parallels between the development of chicken and salmon, and emphasizes that the development for chicken is likely to hold additional lessons for salmon aquaculture. Accordingly, it may provide a useful guide to where salmon aquaculture is likely to go in the future. The discussion will focus on three main aspects: production, supply chain and market.

4.1. Production

In common with most other food production industries, chicken and salmon have their origins in small-scale producers, who made their own inputs, harvested and marketed the animals themselves. However, while the meat-chicken originally was a byproduct of the egg production (USDA, 2016), the salmon industry originated with a specific innovation, the net pen, to exploit an existing market potential.

With the broiler industry separated from the egg production, R&D focused on specifically improving the production process of the chicken for meat. Of particular importance were better breeds and feeds, leading to faster growth and larger birds. Successful producers, specializing in chicken, increased scale as technology developed. In consequence, this facilitated the creation of specialized suppliers for

hatchlings, feed and processing equipment. This process has largely been replicated by the salmon industry through advancements in breeding and by creating a larger and faster growing fish. For both industries this is of course a continuous process and further progress can be expected.

A higher degree of control within the production process allows optimization of more factors. Large-scale chicken production is today conducted indoors in a controlled environment, where the advantages of a controlled environment with respect to higher growth outweigh the cost of providing this environment. Hence, the optimality of environment conditions may be just as important for achieving production efficiency such as genetic advancements through breeding. To a large extent the different factors enhance each other as the controlled temperature, for instance, allows the producer to utilize feed to match the optimal temperature. Control was also necessary to meet the demand for a wider variety of products, and to meet the need for reliability and consistency in quality and cuts. Heterogeneity within product became an undesired feature on the production line as it prevents standardization, which could only be mitigated by clearly defining expectations and dividing responsibilities between farmers and processors.

Relative to chicken, the control over the production process is still quite limited for salmon. This is especially the case when considering the production environment and the level of heterogeneity in the product. The salmon pens are generally placed directly in the ocean where they are prone to varying levels of salinity, temperatures and varying weather conditions (Hansen et al., 1993). However, there are changes predominantly in the smolt production that is now land-based with control over biophysical factors such as water quality, temperature and light (Sandvold and Tveteras, 2014). Substantial research is being conducted to improve the control over the interaction between the pens and the surrounding environment, including research regarding land-based solutions, a technology that has been implemented for other fish species and a hand-full of salmon farms.⁹ Although unclear what the further development will be, there is no doubt that increasing control within the production

⁹ The Netherlands, Denmark and Germany implemented in the late 1980s the first commercial scale land-based closed containment systems for eel production. The sea bass, sea bream, trout, halibut, turbot, tilapia, Arctic char are other examples of species farmed in land-based systems (Pinfeld, 2014).

process will facilitate further productivity growth and production increase, with improved control for diseases as an important by-product.

Ultimately, a higher degree of control over the production system makes it easier to address problems when they arise, and allows for new opportunities as a result of better understanding the needs of the market, as in the case of chicken.

The technological change in both industries has been scale dependent, at the farm level and even more so at the processing level. This is an ongoing process, as in the US, there are now about 50 processing and marketing firms for chicken (Shamshak and Anderson, 2008). Also for salmon, productivity studies report increasing returns to scale (e.g. Roll, 2013; Asche, Roll and Tveteras, 2016), and Asche et al. (2013b) show how the number of companies have been rapidly reduced in all the main salmon producing countries.

4.2. Supply chain and processing

The key factors for the success of the chicken industry are its efficiency and strong focus on reducing time between production and delivery to customers, by improving capacity utilization. Also here, the salmon processing techniques and supply chain developments have progressed in a similar manner as the early stages for chicken. However, salmon still has a long way to go to reach comparable efficiency levels. There appears to be substantial value to be generated from further improving processing steps throughout the supply chain from pre-slaughter to post-slaughter and transportation.

Effective processing influences the appearance, shelf life and quality of the end products, and therefore creates value. Economic efficiency in the broiler industry was achieved by researching new technologies. The quantity and variety of available systems and equipment are good indicators of the progress in the chicken processing. While it is possible to process up to 26,000 broiler chickens per hour in the largest plants, the line speed for salmon fluctuates around 6,500 fish, despite the relative simplicity of a fish's body structure. Within the salmon industry, the systems are relatively basic, with the list of automated actions comprising killing, gutting and filleting.

A large processing plant in Norway, with the capacity to process up to 90,000 fish per working day, will still use manual labor for feeding the fish through the different machinery. This is equivalent to 20-25 employees in the primary processing area alone, performing their duties at any given time during a shift, to work 26 mt of live fish (assuming 4kg fish) every hour. When compared to the live weight that can be processed hourly in a fully automated chicken plant (71 mt, assuming 2.75kg broilers), it becomes clear that the salmon supply chain has substantial room for further development.

The move from labor-intensive practices to a capital-intensive industry doubled the productivity in the broiler industry during the last part of the 20th century (Watts and Kennett, 1995), hence increasing the supply of chicken and reducing prices. When the automation of the chicken processing started in the 1950s, each bird was cut up into eight pieces, without regard to each one's quality. Over time the homogeneity of raw materials created the basis for fine-tuning the processing. Cuts were perfected; with each bird being mechanically graded and assessed to produce the highest possible value during processing (Barbut, 2010). This was due to a combination of flexibility, high yield and consistent output quality in the cut-up systems. On the other hand, within the salmon industry, most steps in the process have remained constant and semi-automatic since the 1990s. Moreover, the cut and weight of the fillets fluctuate, indicating that the industry has not yet reached a level of consistency such as the one for chicken. This may be due to a higher variability in the fish size, which makes it difficult for machinery to produce a homogeneous output. Processing the fish into consistent, reliable fillet products would increase the predictability in the supply chain and allow producers to innovate with respect to value-added products, would create new opportunities for processing industries to emerge, and would provide customers with a clear standard. The processors would, as a result, have the opportunity to further increase the value of the fillets by pricing them on the basis of color, melanin spots and freshness, for example.¹⁰

¹⁰ It is of interest to note that the salmon farmers have learned to manage flesh color, and are optimizing it (Forsberg and Guttormsen, 2006).

For salmon, it remains the standard to allow on average 1.5 hours for chilling, bleeding and washing during the slaughtering process, while the chickens are processed immediately after killing. The difference is in that salmon is chilled before being killed and bled thereafter in large tanks with iced seawater, while the chickens go through a continuous process from stunning, to killing and defeathering, to cut-ups and beyond, all the while being hung upside-down to allow blood drainage by gravitational force. Direct processing techniques have also been investigated for the primary processing of salmon (Roth et al., 2005), although they have not yet been implemented in modern processing plants. In addition, large quantities of water and energy are used in the process for salmon, suggesting potential for efficiency gains.

Conveyor belts and the semi-automated level of processing in the salmon industry make it difficult to individually grade and track the raw material, limiting the degree of flexibility possible. The lack of flexibility also affects how adaptable production is to the market demand. For example, within the chicken industry, the Asian market has a preference for leg meat. Machinery with single shackle hanging technique is normally insufficient to meet this requirement, but it can easily be adapted to double bracket shackling to ensure the final product remains undamaged. The salmon industry will have to overcome bottlenecks from manual interventions, by engineering machinery that mimics the broiler technology and offers product flexibility.

In the early 1980s, ready to cook broiler chickens were transported on ice to retailers (Ang et al., 1982), as salmon is today. The spoilage time for fresh salmon is just over a week when kept on ice, while for chicken it is between 11 and 14 days, depending on the handling method. The chicken industry has moved toward the more effective practice of super-cooling and special packaging forms, as well as requiring the broiler farms to be located within miles of key facilities that ultimately allow for a longer shelf life and increased freshness.¹¹ Similar technologies have also been tested for fish as early as 1920 (Le Danois, 1920), but are not used for salmon processing despite research showing that shelf life can be increased two-fold (Aune, 2003).

¹¹ Super-cooling refers to the storage of food products at temperatures just above their initial freezing point. These temperatures must strike a balance between reduced bacterial activity and reduced formation of ice crystals.

For the salmon industry to match chicken in efficiency, it must move further away from the traditional supply chain model. A number of innovations must still take place before this milestone can be achieved, notably the automation of the primary processing techniques, a reform of the processing lines, and embracing already existing techniques that can support the current transportation means.

4.3. Market

Chicken has grown in popularity with consumers because of its lean meat, a trend also noticed in the narrowing gap between per capita consumption of chicken and the red meats (Shamshak and Anderson, 2008). Similarly, salmon has moved from being a luxury product with limited quantities to a product available for most consumers. However, salmon consumption is still limited compared to that of chicken.

Perhaps one of the most notable successes of the broiler industry is the creation of new products and distribution channels. The emergence of added value products drove further market expansion for the broiler industry, as chicken products were adapted for new consumption and use settings. The breast cartilage, an initially unlikely value product candidate, is in demand by pharmaceutical companies for its properties (Schwartz and Park, 2012; Wei et al., 2009) and, as a result, has become a standard cut. By contrast, the salmon product variety, and hence distribution channels, are still relatively poor (Figure 7). Fillets are the most common cuts on the market, whether they are fresh, frozen or smoked. The salmon product launches on a yearly basis are half the number of the chicken product launches (Asche and Guttormsen, 2014). We hypothesize that this is a consequence of the poor technological developments in machinery for cutting and deboning, and poor handling of waste.

The feasibility of using trimmings and cut-offs for the creation of new products is largely a function of scale. Once the production and processing plant operations become sufficiently large, further processing also becomes economically viable. For example, in the 1990s, before waste products started to be used for fish meal and silage, it was costly for the salmon industry to discard this biomass, a situation similar to that in the early on for the chicken industry.

Comparing the market innovations in the chicken industry against those for salmon, it becomes clear that the latter is lagging far behind, particularly in terms of highly processed products. There are opportunities for market expansion through the creation of a more diverse range of products. Also here, the salmon industry is moving in the right direction with a growing product specter leading to increased demand (Asche et al., 2011; Brækkan and Thyholdt, 2014). However, the chicken industry and especially the value added product forms provide an indication of the market potential.

5. CONCLUSIONS

The development of the chicken industry into the intensive production system it is today is a consequence of having gained a high level of control over its production processes. Innovation triggered substantial productivity growth in this industry, concomitantly boosting profits and offering growth opportunities for new related industries.

The growth in the salmon aquaculture has experienced a similar development as chicken with the development of specialized suppliers, breeding programs and more advanced marketing. However, the industry lags substantially behind the chicken industry over a number of dimensions. In this paper we highlighted existing gaps in production, processing and supply chain, and marketing relative to the broiler industry. The fact that the knowledge and technology exist for chicken implies that there is still a tremendous potential for salmon aquaculture to continue to grow by adopting more of these. Hence, the lack of sophistication in knowledge use throughout the supply chain is, if anything, an opportunity for salmon aquaculture.

It is worthwhile to note that knowledge transfer from the chicken industry is not necessarily straightforward. One essential element with respect to when the knowledge is transferred relates to the scale of the industry. Increasing scale will help create a market for specialized suppliers to implement this knowledge into technology and services (Asche, 2008). Moreover, as the easiest transfers most likely already have occurred, future transfers will be more costly and will require more R&D to transfer further insights.

This qualitative comparison is also relevant to other aquaculture species that are characterized by still more limited use of knowledge in terms of biological understanding, production technology, supply chain, product development and markets.¹² In this context it is worthwhile to note that Kobayashi et al. (2015) not only forecast an aquaculture production of 93 million mt in 2030, but that their simulation indicates that it is unlikely to happen with a much lower production, and more likely with a substantially higher production. This uncertainty reflects the extent to which productivity will increase. The insight from this paper is that additional productivity enhancement in aquaculture species will depend on how much knowledge is adopted from salmon aquaculture and other food production systems such as chicken.

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¹² Some examples are provided by Little et al. (2016) and Pincinato and Asche (2016).

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