A BIOECONOMIC MODEL OF INDOOR PACIFIC WHITELEG SHRIMP (*LITOPENAEUS VANNAMEI*) FARMS WITH LOW-COST SALT MIXTURES

by

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To my friends and family whose unwavering support made this possible, but especially:
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ABSTRACT

Marine shrimp production in indoor facilities that utilize Recirculating Aquaculture Systems (RAS) have become increasingly popular in the Midwestern U.S. due to their ability to have year-round production. The problem with these inland shrimp RAS farms is that they are located hundreds of miles from the ocean and farmers must create the sea water growing medium by mixing freshwater with specialized, expensive sea salt. Recent studies on Low-Cost Salt Mixtures (LCSMs) derived from cheaper, industrial salt components have shown promise. This study analyzed the impact of these LCSMs on a commercial RAS system using a bioeconomic model. The model was constructed with biological growth parameters and financial and capital costs to obtain a series of financial performance measures.

Commercial farms in the Midwestern U.S. provided data to validate the model's inputs. The Aquaculture Research Center at Kentucky State University provided data where commercial data was lacking. Using Palisade's @Risk excel add-in, a series of biological and cost variables were made stochastic using the triangular distribution, with the key output variable (KOV) being the farm's net present value (NPV). Three separate farm scenarios were analyzed: 8-tank growing system, 16-tank growing system, and 24-tank growing system with each farm replacing 100% of their water and reapplying salt after every sixth crop's harvest.

A series of stress tests conducted on the stochastic variables controlling for survival rate percentage, electricity usage, discount rate, and selling price revealed each system's overall vulnerability to fluctuations in these variables. The adoption of the LCSMs did improve each scenario's mean NPV significantly. Other inputs such as electricity usage, selling price, and annual survival rates had significant effects on each farm scenario – most notably the selling price. Smaller RAS farms like the 8-tank system are far more vulnerable to fluctuations in the key input variables in comparison to the larger farms. The study found that scaling up in size and the increased adoption of LCSMs can help reduce the overall risk for RAS shrimp farms.

CHAPTER 1 – INTRODUCTION

Decreasing ocean stocks and an increasing demand for seafood have led to a rise in global aquaculture production. Aquaculture is the world's fastest growing food-producing sector and currently produces about 50% of global food fish (NOAA, 2020). The U.S. is the 4th largest global exporter of seafood and the largest importer of seafood by value (FAO, 2019). In 2018, the U.S. imported over six billion pounds of edible seafood products worth an estimated $22.4 billion (NOAA, 2020). Shrimp comprised 28% of the total dollar value of these imports and 25% of the overall weight (NOAA, 2020).

Shrimp aquaculture has its origins in Southeast Asia where farmers raised small crops of shrimp in tidal ponds beginning as early as 1759 (Tidwell, 2012). Starting in the 1930s and continuing through the 20th century, various scientists across Asia and the U.S. began exploring different rearing methods, technologies, and practices aimed at cultivating shrimp on a commercial scale. Beginning in the 1960s, Japan and Taiwan began investing heavily in research and its applications to growing shrimp on a large scale. By 1985, Taiwan's production reached nearly 45,000 metric tons alone and by 1986, global production totaled 148,000 metric tons. Taiwan's success and methods were replicated by neighboring countries including Thailand, Malaysia, and Indonesia (Tidwell, 2012). According to the most recent report on global farmed shrimp by the Food and Agriculture Organization of The United Nations (FAO), an estimated 3 million tons of farmed shrimp entered the market in 2018 (FAO, 2019).

The most common farmed shrimp is the Pacific Whiteleg Shrimp (*Litopenaeus vannamei*), which is a tropical marine shrimp that is native to the Eastern Pacific coast from Mexico to Peru (FAO, 2006). Adolescents and young adults spend most of their life in coastal, brackish estuaries but choose to spawn and spend most of their adult life in the open ocean (FAO, 2006). It is the principal species of both outdoor pond and Recirculating Aquaculture System (RAS)[1] production worldwide accounting for nearly half of global shrimp production in 2017 alone (FAO, 2019). The U.S. is a small player in terms of shrimp production compared to countries in South America and Asia, but it has been an active participant in furthering research

[1] Recirculating aquaculture systems recycle all or part of the water used in the production system and are usually used under intensive cultivation methods.

and commercial capabilities at both a private and governmental level. Coca-Cola and DOW Chemical were some of the companies that invested in research and commercial expansion of the shrimp industry in the 20th century (Tidwell, 2012). The USDA also established the US Marine Shrimp Farming Program in the 1980s that continued to fund shrimp aquaculture research until it was disbanded in 2011 (Tidwell, 2012). The lack of support for domestic shrimp production led to countries in South America and Asia expanding their production capacity.

In recent years, there is renewed interest in shrimp production in the U.S. There have been numerous investigative reports published describing abhorrent working conditions in the Southeast Asian shrimp industry including a 2015 publication by the Associated Press entitled "Global Supermarkets Selling Shrimp Peeled by Slaves" (Mason et al., 2016). This specific publication was part of a compilation of stories on the Southeast Asian shrimp industry that won the Pulitzer Prize for Public Service. Similar stories have led to calls to boycott shrimp from Southeast Asian countries and have created opportunities for domestic shrimp production for the local market. Despite this opportunity, domestic shrimp producers remain at a severe disadvantage from a marketing and pricing perspective. Not only are U.S. producers competing against cheaper farm-raised imports, they are also competing against wild-caught, domestic shrimp as well.

In the U.S., marine shrimp are grown in ponds and RAS. It is very common for farmers to use hybrid systems. RAS require more investment and active management due to their mechanical nature, and even though there has been well over 20 years of research on RAS farms, there is still very little research in the area of economic analysis. The lack of research is due to a multitude of local and international factors. In particular, the commercial shrimp industry experienced a significant die-off in the 1990s due to virulent pathogens making their way into commercial ponds all over the globe. Many of the U.S. farms and hatcheries at that time were forced to shut down or elected to move overseas where costs were lower, and the climate was more favorable. Although most of these farms were pond oriented and not RAS, the global industry was able to recover at a faster rate in comparison to the U.S. with disease resistant *L. vannamei* stocks (Tidwell, 2012).

There has been very little or no information on commercial success of large-scale shrimp operations nor has there been any substantive economic research on costs, production, or likelihood of success, which is needed for informed decision making by prospective farmers and investors interested in building shrimp RAS farms. The goal of this project is therefore to provide some insights into some of the costs of shrimp RAS farms and examine their overall economic viability.

The objectives of this thesis are to:

1. Develop a bioeconomic model that incorporates biological growth data, operational costs, and variable costs to assess a series of financial performance measures
2. Analyze the economic performance of low-cost salt mixtures (LCSMs) on the financial performance of inland, U.S. recirculating aquaculture system (RAS) *L. vannamei* farms
3. Deliver results to current and prospective stakeholders including farmers, investors, and researchers interested in *L. vannamei* RAS shrimp production.

There have been several economic research studies in the field of aquaculture, but very little in RAS shrimp farming in the US. There has been increased interest in RAS shrimp production in recent years, but many farms have struggled to stay in business. It is the goal of this paper to incorporate current economic and biological data from both research facilities and commercial farmers into a comprehensive, stochastic model to estimate the economic feasibility of these systems. The study runs a series of sensitivity and stress analyses on key input parameters including the cost of salt.

RAS shrimp production is capital intensive and one way for farmers to increase profits is to reduce costs. Several key input costs for RAS farms such as feed, electricity, and labor are subject to external forces and cannot be easily controlled. The LCSM used in this study is composed of readily available, cheaper salts and could be a seamless, effective solution to alleviating financial pressure on farmers.

Results from this study could have a tremendous impact on the industry's profitability and future growth. As production costs fall and prices remain high for RAS-grown shrimp, more people may be encouraged to enter the market and increase domestic production. This could lead to an increase in local jobs, an improved local food system, and a reduction in the U.S. seafood trade deficit. Inland communities in the U.S. are located hundreds or thousands of miles away from the ocean and lack consistent supply of fresh seafood. An increase in RAS farms could provide rural, inland communities with a more sustainable, local, fresh protein source. Local, fresh seafood could also have a direct impact on the health of local communities.

CHAPTER 2 - BACKGROUND AND LITERATURE REVIEW

2.1 Shrimp Markets

In 2018, total U.S. commercial landings of wild shrimp totaled 289.2 million pounds valued at $496 million (NOAA, 2020). Wild-caught, commercial landings of shrimp in the U.S. have remained largely stagnant the last decade while imports have increased over the years (Figure 1). The quantity of shrimp imported in 2018 totaled 1.5 billion pounds amounting to 28% of the total value of all edible seafood imports, which was an increase of 68.6 million pounds from 2017 (Figure 2). Of the 1.5 billion pounds of imported shrimp, more than 78% came from Asia. Ecuador, the largest non-Asian exporter to the U.S., exported 167 million pounds accounting for roughly 11% of U.S. shrimp imports by volume. India alone imported 545 million pounds comprising over 35% of total shrimp imports by volume (NOAA, 2020). In terms of volume of all U.S. edible seafood imports, shrimp accounts for 25%, second after fish fillets, which accounts for 26% (Figure 3).

Figure 1 - U.S. Supply of Shrimp, 2009-2018

Source: (NOAA, 2020)

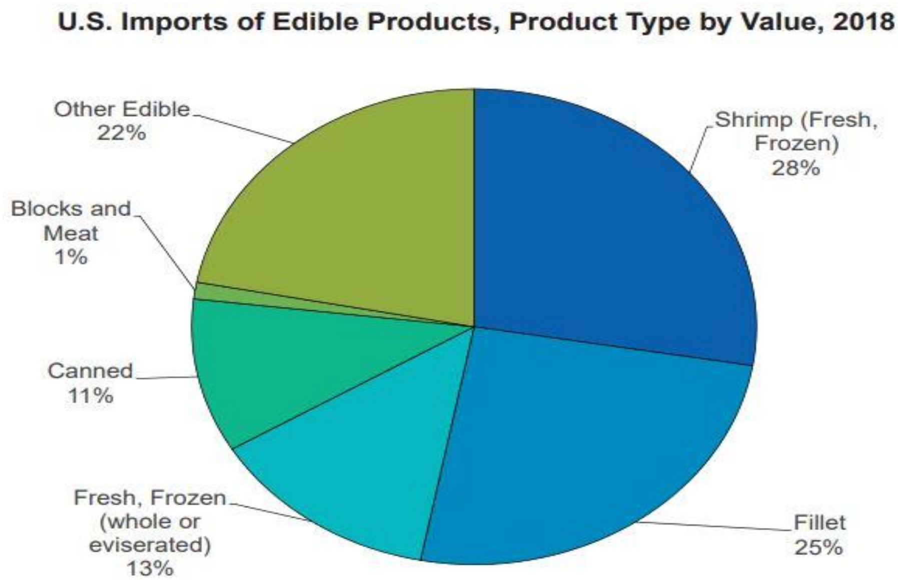

Figure 2 - U.S. Imports of Edible Products, Product Type by Value

Source: (NOAA, 2020)

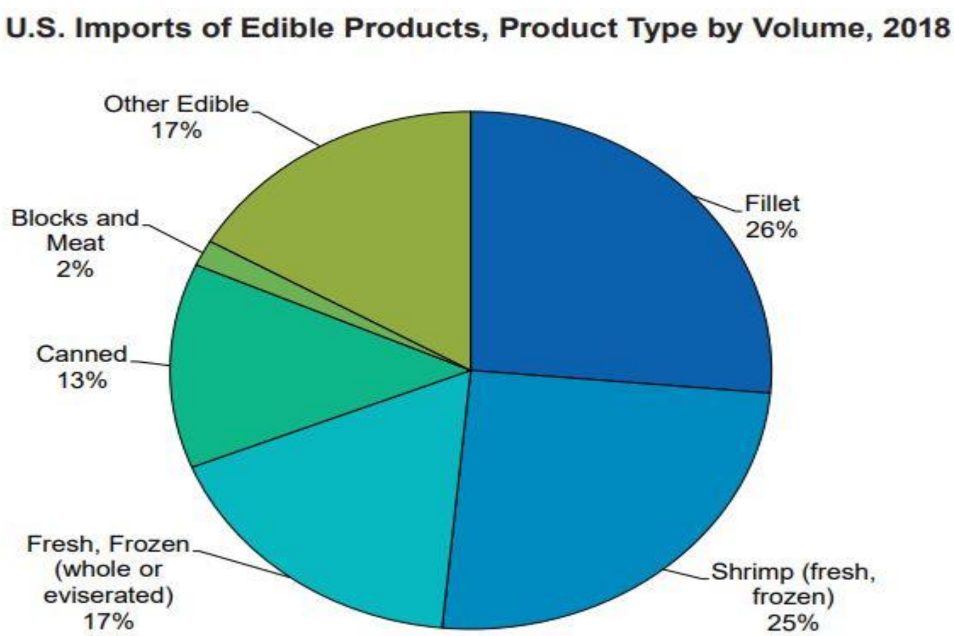

Figure 3 - U.S. Imports of Edible Products, Product Type by Volume

Source: (NOAA, 2020)

The recent Census of Aquaculture data indicates total aquaculture shrimp production valued at $45.6 million (U.S. Department of Agriculture, 2019). Shrimp sold in the U.S. can be divided into two categories: Farm-raised and wild caught. Both can be sold in a variety of ways: Whole, head-off, head-off and tail-off, peeled and deveined, peeled and deveined with the tail, butterflied, etc.

Shrimp consumption in the U.S. has increased by more than 130% between 1985 and 2018, from 2.0 pounds to 4.6 pounds per person (Figure 4). It's an easy-to-cook protein source that can be eaten in a multitude of ways. It is easy to clean and cooks quickly. With the availability of wild shrimp stocks from all three coasts, American consumers are well acquainted with it and do not need to be convinced into purchasing shrimp. Without the need for extensive marketing, the barriers to entry into the U.S. market have been low for overseas producers. Diet trends have also shifted to protein-heavy diets making shrimp an attractive choice for health-conscious consumers due to both its affordability and accessibility.

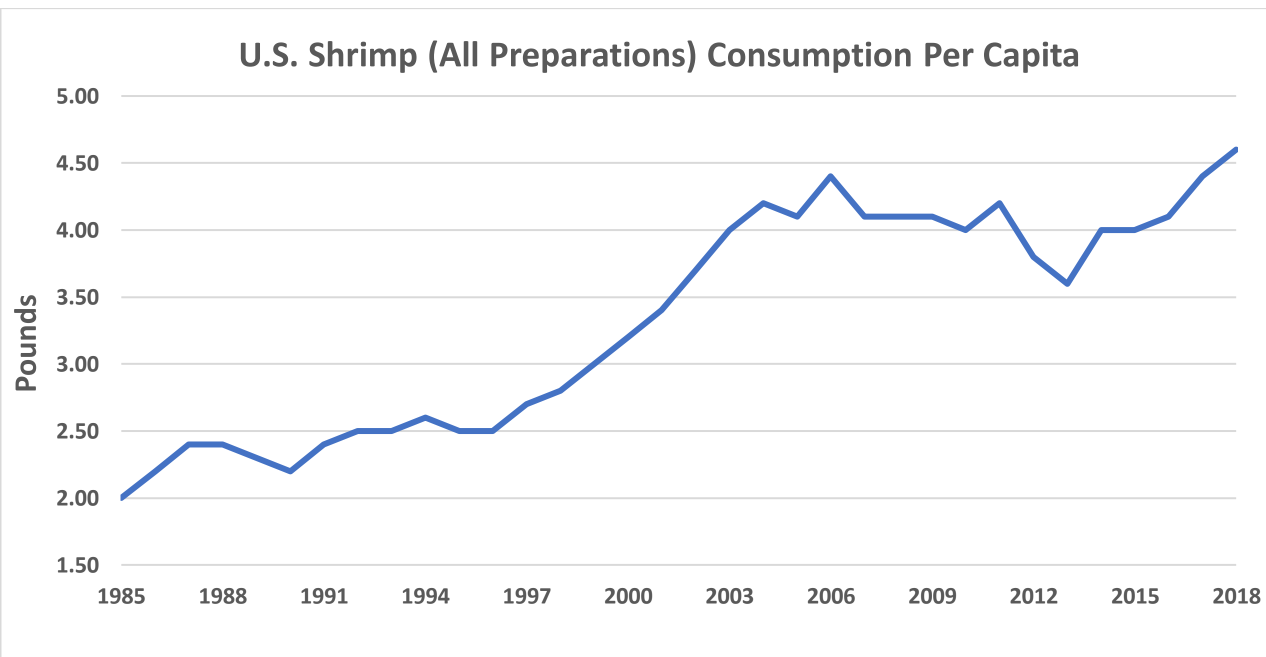

Figure 4 - U.S. Shrimp (All Preparations) Consumption Per Capita

Source: (NOAA, 2020)

Ortega et al., (2014) conducted a willingness-to-pay (WTP) study aimed at gauging U.S. consumer's attitudes towards food production practices associated with various aquaculture products. The authors find that U.S. consumers are willing to pay: $10.65/lb for an enhanced food safety characteristic and $9.83/lb for the absence of antibiotics in U.S-grown shrimp. The WTP for imported shrimp from China and Thailand with an enhanced food safety characteristic was $3.71/lb and $4.12/lb respectively. The WTP for an absence of antibiotics in shrimp imported from China and Thailand was $1.97/lb and $2.84/lb respectively. Although this study is more focused on the attributes associated with the shrimp's production methods, U.S. consumers are willing to pay more for substitute goods – in this case, farm-raised shrimp. American shrimp farmers using RAS can lay claim to both attributes, but the challenge remains to keep production costs down to compete at the $10.65/lb price tag reported from the above study.

Asche et al., (2012) conducted a study examining the long-term viability of the U.S. wild caught shrimp fishery and the degree of market integration. Wild shrimp fisheries in the U.S. are located in the Gulf of Mexico and are vulnerable to supply shocks relating to weather, oil spills, and the possible reduction in annual catch quotas. The study used data on both domestic and imported shrimp prices and found evidence to support the notion of market integration between the two products. This means that when the domestic wild-caught shrimp faces supply shocks, the price of shrimp does not rise to offset the shock. Instead, imports increase to fill the void. The authors argue that if the U.S. were to enact trade restrictions with the intention of benefitting domestic suppliers, market integration suggests that imports would still increase, but from countries exempt from the trade restrictions. If the shrimp market is integrated as this study proposes, then there is an opportunity for domestic suppliers to fill the void left by supply shocks to importers.

2.2 U.S. RAS Shrimp Production

L. vannamei production occurs in three stages: Hatchery, nursery, and grow-out with each phase requiring different levels of technology, investment, and managerial oversight. Most farmers begin production at the nursery and grow-out stages, opting to purchase juvenile shrimp from specialized hatcheries.

The first stage of production is the hatchery phase. This is where shrimp eggs are procured and hatched using female broodstock (Whetstone et al., 2002). Two methods of hatching shrimp larvae from female eggs were developed in the mid-20th century. The "Galveston" method, generated by a team of researchers led by Harry Cook in Galveston, Texas used clear water, smaller tanks, and regimented feeding times (Tidwell, 2012). The other method was developed by a team of researchers in Japan and Taiwan that used larger, deeper rearing tanks and grew several species of algae simultaneously. The algae's growth gave the water a green complexion, thus the method became known as the "The Green Water" method (Tidwell, 2012). Commercial hatcheries utilized practices from both methods.

The hatchery phase begins with broodstock egg-laying females. These are either curated from the production crop or captured from the wild (FAO, 2006). They are often stocked in dark tanks using filtered seawater. Using various methods, females of 8-10 months of age can be made to reproduce efficiently under a controlled environment (FAO, 2006). Females can produce up to 100,000-250,000 eggs per hatch (FAO, 2006). Once the females release their eggs, they are then fertilized, reared, and hatched. The resulting nauplii, the term used to describe first larval stage, are then transferred to a larger tank to begin feeding and grow out. Domestic hatcheries often raise their nauplii to a size of around 0.004 grams at which point they are sent to the farmer's grow out location. The hatchery phase requires a significant level of investment in comparison to the nursery and grow-out phases.

The nursery phase involves rearing the 0.004g nauplii to a larger shrimp. RAS farmers often raise their nauplii to a 1.0g post-larvae (PL). The role of the nursery phase is to both acclimate the nauplii to the lower salinity levels of the grow-out phase and accelerate growth thus ensuring a higher likelihood of survival. The PLs are also fed a diet that is higher in protein in comparison to the hatchery phase. The nauplii arrive from the hatchery in full strength seawater which amounts to around 30 ppt of salinity. RAS farmers in the U.S. often dedicate a specific tank for nursery rearing and transfer the shrimp to the grow-out tanks once they reach the necessary stocking size. Stocking density, the amount of shrimp per cubic meter of tank space, is considerably higher in the nursery phase in comparison to the grow-out phase. During this phase, the farmer hopes to both acclimate the shrimp to the system and grow them to a larger size in the grow-out phase. Another option for farmers is to bypass the nursery phase altogether and buy 1.0g PLs from a hatchery. Of course, these PLs are more expensive and it becomes a question of supply and assessing whether the capital investment and variable costs of running a nursery operation outweigh the higher cost of directly purchasing larger PLs.

The grow out phase may be in ponds and/or recirculating aquaculture systems (RAS). Ponds in the U.S. are simple in nature and are created by diverting natural, salinized water from underground aquifers. This is common in certain parts of the Southern U.S. In contrast, most RAS farms are located inland, hundreds of miles from the ocean and hence must simulate a contained, controllable aquatic ecosystem. Stocking density is significantly higher in RAS compared to ponds and has a significant impact on the management practices. In a natural pond aquatic environment, the rhythmic ebb and flow of water provides nourishment and oxygen to shrimp while neutralizing toxic elements.

Ammonia is excreted by shrimp through their feces and can also accumulate in RAS production from excessive feed particulates (Schuler et al., 2010). Maintaining water quality and reducing toxic, nitrogenous compounds such as ammonia, that accumulate due to the higher number of animals per unit of space is paramount**.** Ponds accomplish this by exchanging water at a greater rate (pumping water in from the underground aquifer and pumping out) while RAS utilizes engineering and technology. One option is to actively remove toxic elements via biofiltration. This is achieved by filtering the farm's water through a series of microbial media. This bacteria's main function is to consume these nitrites and return the water to a more favorable pH level. Another option for RAS farms is to use a bio-floc system. This is a more passive way of recreating a natural marine environment. Limiting water exchange and removal of the accumulated particulates allows for the creation of bioflocs which are, "aggregates of algae, bacteria, protozoans, and other kinds of particulate organic matter such as feces and uneaten feed" (Hargreaves, 2013). These bioflocs are solid masses that can be seen with the naked eye and can act as supplemental nutrition for shrimp between feeding. This blend of microorganisms can also provide a natural way of cleaning and removing toxic elements. RAS production in the United States is still a very young industry and there remains no 'tried and true' way of optimizing water quality and production. It is very common for farmers to use hybrid systems.

In the grow-out phase, the harvested PL shrimp from the nursery phase is stocked in another tank where it grows over the course of several weeks to a market sized shrimp. The stocking density is often measured in the number of PLs per cubic meter of volume. For example, a stocking density of 300 PLs/cubic meter within a 15 cubic meter tank would amount to a 4500 PLs/grow-out tank. Valderrama and Engle (2002) conducted a study on Honduran shrimp farmers using a linear programming model based on farm production records. They assumed that stocking density had a negative effect on growth and find that low and intermediate stocking densities resulted in a reduction in annual risk. Stocking density, desired market size, and biological factors including growth and survival are important to a farm's success.

Domestic RAS farms face higher production costs and stricter environmental regulations in comparison to foreign producers and lack access to federal research grant opportunities that could make them more competitive. According to Love et al., (2017), federal aquaculture grant funding comprised only 0.03% of the $2.73 trillion spent on federal research and development between the years 1990 and 2015. During that same period agriculture, natural resources and environment, and general/basic science received 2%, 1.8%, and 5.9% in federal research and development money respectively. Of the $1 billion allocated to aquaculture grants between 1990 and 2015, one third of it supported research on microalgae, primarily for biofuel purposes. Although marine shrimp were one of the top five species in allocated grant money (average of six grants per year) during this time period, the grants were mainly focused on genetics, breeding, and pathogen research as opposed to downstream sectors such as economics or marketing.

Despite these inherent disadvantages, there are opportunities for U.S. producers to be profitable. With higher costs, domestic producers will have to charge a higher price, focusing on niche markets. Some farms sell to high end establishments, while others have had success selling fresh shrimp directly to consumers either on site or at farmer's markets. Due to the comparative advantage of shrimp production abroad, it is unlikely that the U.S. will be able to compete directly with overseas producers. But if these large, overseas farms were to encounter a massive supply shock due to disease outbreak, natural disasters, or trade disputes, local U.S. producers could benefit. There could also be an increase in demand as consumers begin to place a higher value on locally produced food.

There are advantages and disadvantages associated with RAS shrimp farming. They require far more in start-up and operating costs. This can create a high barrier to entry for some farmers. Another disadvantage is the complexity of the systems themselves. The electrical, mechanical, and biological intricacies can be hard to manage, even for farmers with aquaculture management experience. However, there are numerous advantages to RAS shrimp farming. RAS farms can produce shrimp year-round due to the temperature-controlled environment. RAS farms are not limited geographically and can be constructed and operated anywhere. They also require a greater deal of biosecurity, reducing the risk of exposure to waterborne pathogens. Most of the RAS systems in the U.S. are biofloc systems. These systems are vulnerable to nitrate accumulation and may require an additional nitrate filter to remove it. This being a somewhat nascent industry, there is no industry standard model for biofloc RAS systems - water exchange levels, filtration methods, tank size, and management practices vary across the industry. This lack of information and standard operating procedures can be discouraging for institutional investors.

There are advantages and disadvantages to pond production as well. The biggest advantage of pond production is that they are cheaper to construct and operate. Pond producers have also been the beneficiary of years of academic research on pond aquaculture in general to support current and future stakeholders. Some of the disadvantages of pond production is that they must be built in warmer areas. Ponds also exchange water at a far greater rate making them more vulnerable to disease pathogens (Moss and Leung, 2006). As discussed previously, the commercial shrimp industry underwent a significant die-off in the 1990s at the hands of virulent pathogens making their way into commercial ponds all over the globe.

2.3 Bioeconomic Modeling and Sensitivity Analysis in Aquaculture

Bioeconomics is the basis of agricultural enterprise. For a farmer to be successful, they must ensure that their crop survives. For a crop to survive, the farmer must possess a thorough understanding of its biological nature: nutrition, seasonality, fertilizer, disease remedies, and growth cycles. Farmers must also be adept at understanding the economics of the operation such as costs and markets. A successful farmer will navigate these two areas with precision and maximize profit given the scarcity of resources at their disposal. A bioeconomic model melds the two together by taking biological data as an input and generating an output that can be used to gauge the farm's overall performance.

There has been a fair amount of research done on bioeconomic modeling of shrimp farms, however most of the research has focused on large-scale, outdoor pond production as opposed to indoor RAS farms. Global shrimp farming is primarily done in large, outdoor ponds so it is not entirely surprising that the community of research surrounds this mode of production. Valderrama and Engle (2001) examines the inherent risk associated with pond farmers in Honduras and analyzes their profitability through certain risk scenarios. The authors gathered data from 21 farms relating to costs of production in addition to input parameters such as feed conversion ratio, stocking density, and feeding rates, disqualifying any "artisanal" producers (<10 hectares). The authors create three farm scenarios based on total hectares in production: small (10-150 ha), medium (150-400 ha), and large (>400 ha). They then created enterprise budgets for each of these scenarios and performed Monte Carlo simulations using a series of distributions on key variables within the budgets. This article is relevant to this study in several ways. Valderrama and Engle (2001) attempts to model a production system that at the time was relatively nascent and was working with limited data as in this study. The present study also creates multiple farm scenarios, relies on stochastic modeling, and uses many of the same distributions applied in Valderrama and Engle (2001). Although the mode of production, the size of the farms sampled, and subsequent analyses differ, the bioeconomic methodology, simulation methodology, and distributions chosen are very similar.

Bioeconomic models have also been used to research the production and viability of other species. Ionno et al., (2006) model a series of trout farm production scenarios and generate a series of financial performance measures such as internal rate of return (IRR), net present values (NPV), and payback period (PP). The authors use actual commercial data from an existing RAS trout farm in Australia. The study finds that economies of scale are vital to the financial viability of RAS farms but also find that the NPVs of the different scenarios are largely negative. Although this study does not use stochastic simulations, the model's key variables, outputs, assumptions, 10-year production schedule, and use of commercial data are applied in this paper.

The Hansen-Posadas Bioeconomic Model, the model used in this paper, can be used to assess the economic feasibility of RAS shrimp systems (Posadas and Hanson, 2006). It utilizes a series of biological parameters, capital costs, variable costs, and shrimp prices to generate a series of financial and economic performance measures including yearly cash flows, NPV, IRR, and total costs of production. The biological parameters include growth rates, survival rates, stocking and harvesting sizes. Zhou (2007) utilizes this model to create an inventory and net profit maximization tool to decide the optimal harvest week for prospective shrimp farmers. The paper utilized experimental data from the Gulf Coast Research Lab, the Waddell Mariculture Center, and the Oceanic Institute. Each facility conducted various experiments on shrimp growth using various stocking densities and monitored feed use as well as growth. Using this data along with historic shrimp prices, Zhou (2007) was able to formulate an optimal harvesting strategy to achieve maximum net revenue. Moss and Leung (2006) also utilized the Hanson-Posadas Model to compare costs of shrimp production between earthen ponds and RAS. The RAS facility they modeled was large, comprising 80 individual raceway tanks that are 54.9 m long, 9.1 m wide, and 1.3 m deep. The pond system consisted of 10 each 2.02-hectare ponds. Using Crystal Ball, an Excel add-in, they designated growth rates, harvest weights, feed conversion ratios, and survival rates for the respective systems as stochastic utilizing either triangular or uniform distributions. The authors also incorporated a sensitivity analysis using total cost per kilogram of harvested shrimp as the key output variable. They found that survival was the biggest contributor to variation in total cost for the ponds, while the key contributors to cost variation for the RAS farms were evenly spread among survival and weekly growth rates.

Sensitivity analysis can be interpreted as the weight each individual input carries when calculating the designated output's value. When using Monte Carlo simulation and stochastic variables, the sensitivity analysis is a critical step in analyzing the strengths, weaknesses, risks, and opportunities of the scenario being modeled. Researchers in aquaculture rely heavily on stochastic simulation and sensitivity analysis to model production, risks, opportunities, and weaknesses. Trapani et al., (2014) compare two different methods of oceanic sea bass production: inshore and offshore. Each method comes with different levels of production, investment, and management. The key output variables in the study are IRR, NPV, and discounted PP (the number of years it takes for discounted cash-flows to equal initial investment costs. Trapani et. al., (2014) find that offshore production yielded superior economic profitability. The authors perform a sensitivity analysis assuming 5, 10, and 15% increases on the cost of fingerlings, the cost of feed, and the sales price of the sea bass. Increases in feed and fingerling costs did adversely affect both systems but are not a strong indicator of financial performance in comparison to one another. The sales price has a more significant effect on both production scenarios, with the offshore system containing less variation in its NPV. Ligeon et al., (2004) incorporate bioeconomic modeling and sensitivity analysis on catfish production to calculate various financial performance measures such as NPV and Break-Even Point for several production scenarios. The authors examine the changes to these measures after incremental increases in feed prices. Dame (2018) examines internal and external risks associated with Florida oyster production. The author incorporates sensitivity analysis to see which risk event has the greatest impact on overall financial profitability.

A stress test is used to determine the ability of a certain asset to withstand a shock, or incremental change in one of its inputs. When employing stochastic processes, the input variables that are generated are a result of both the type of distribution and the values specified. Stress testing allows for greater scenario analysis by designating a specific range of the distribution that the values can be drawn from. Sorge and Velalainen (2006) examine different stress testing methodologies on macroeconomic variables within Finnish banking portfolios. Although complicated and not explicitly agriculture or aquaculture-related, the method of examining the probability of returns and calculating risk are employed in this study.

Palisade’s @Risk Software and Monte Carlo Simulation are both very popular in applied economics research. @Risk is a Microsoft Excel add-in made by Palisade that is dedicated to risk and decision analysis (Palisade, 2019). There have been numerous academic papers and industry case studies using @Risk as their principle analysis software. It is commonly applied in the aquaculture economics partly due to the field’s relative nascence and lack of long-term data in comparison to other forms of commercial agriculture. Lipton and Kim (2007) conduct a study comparing the economic feasibility of inshore vs. offshore rock bream fish production. Data were collected for both means of production and the NPV was computed over a ten-year period. Uncertainties of financial performance and overall production were captured using Monte Carlo simulation. With an assortment of data including a pilot farm for offshore production, the authors utilize triangular distributions for their key variables to assess the financial viability of both systems. The authors also utilize sensitivity analysis on the various inputs to assess each system’s vulnerabilities and probabilities of success. Jolly et al., (2009) employs @Risk to assess financial performance measures such as NPV and IRR within small-scale, Asian aquaculture producers. Medley et al., (1994) also uses @Risk to assess the economic feasibility of raising Australian Red Claw Crayfish in the U.S. Enterprise budgets for different production scenarios were created, and an assortment of variables were made stochastic using primarily triangular distributions within each budget. The total value of the crayfish was calculated on a per hectare basis with the output variable being net returns to management.

Bisesi (2007) examines the efficacy of non-sea-salt ionic solutions in *L. vannamei* pond production. Written from a biological perspective, this study examined growth, survival, total harvest weight, and feed conversion ratios. Bisesi (2007) includes a brief economic section detailing the potential savings pond farmers could expect if switching from the regular sea salt to the cheaper, non-sea-salt mixture being studied. The author found that if a farmer decided to completely switch to the non-sea-salt alternative, they could potentially save ~$70,000 for each stocked pond.

Many of the economic studies on RAS shrimp draw their data from academic research settings for several reasons. The first being, that RAS shrimp farming is very small and lacks commercial operations to provide data. Another reason is that aquaculture researchers have a thorough understanding of the science behind RAS production and proper management. Unfortunately, many small-scale RAS shrimp operations are supplemental enterprises and the farmers have little or no training in aquaculture production. Using data from only research settings can be misleading in that it fails to capture the variations in commercial RAS farm management and the effect on overall farm performance. The model farms in many of the studies are considerably larger than what the current industry resembles. The combination of using data from research and commercial farms for RAS shrimp farming is more appropriate to understand the commercial viability. RAS shrimp farming is a relatively new industry with few commercial farms, therefore this paper attempts to combine both experimental and commercial data to better capture the variations in RAS shrimp farming that resemble the current industry.

CHAPTER 3 - METHODS AND FRAMEWORK

3.1 Model Framework

This analysis uses a modified version of the Hansen-Posadas Bioeconomic model created by Dr. Terry Hanson and Dr. Benedict Posadas (Posadas and Hanson, 2006). The model comprises an excel spreadsheet model that considers an extensive list of biological parameters, variable costs, and capital costs and generates an assortment of financial and economic performance measures (Figure 5). The model is interactive in that there are multiple worksheets. The worksheets are generated by biological parameters and costs that are manually entered by the user. These include the biological parameters: Survival rate (%), weekly growth rate (grams), stocking size (grams), and desired harvest size (grams). Data entered also includes capital and variable costs including overall investment, feed costs, energy costs, labor costs, PL costs, borrowing rates, tax rates, and selling price per pound. The model's outputs include the net present value, stocking and harvesting schedules, monthly and yearly cash-flows, itemized costs, and power usage. Zhou, (2007) discusses the mathematical computations and functions implemented in this model. It also assumes that the farm will receive consistent supply of PLs for stocking purposes and that all the shrimp produced will be sold at the price designated for the given year. It also assumes that the farm will produce continuous crops.

The model also considers the option of implementing a nursery. This requires separate parameters that are manually input by the user. If the user decides to bypass the nursery stage of production and source larger PLs for the grow-out stage, the model will not incorporate the production and cost inputs for the nursery section. It is assumed that a nursery in this context is simply additional tank(s). It is not uncommon for larger, commercial aquaculture operations to have designated buildings or facilities for each stage of production, but in this study the nursery stage is assumed to take place in a single facility. All scenarios in this study do incorporate a nursery stage.

MODEL DESIGN

Manual Inputs

Biological Parameters	Facility Specifications	Costs	Price
Survival Percentage	Number of Tanks	Salt	Selling Price per lb
Stocking Density	Tank Dimensions	Feed	
Weekly Growth Rate	Desired Salt Levels	Electricity	
Stocking Size	Production Area	Labor	
Target Size	Water Levels	Construction Costs	
Feed Conversion Rate		PLs	

Outputs

Input Analysis	Maintanence and Depreciation	Production	Financial Performance Measures
Feed	150% MACRS Schedule	Capacity	Itemized Costs
Salt	Maintanence Schedule	Yearly Breakdown	Yearly Cash-Flows
Labor			Net Present Value
Electricity			Sesitivity Analyses
Water			Stress Analyses

Figure 5 - Model Design

3.2 Model Calculations

Equation 1 calculates the length of each production cycle. All three of the inputs in this equation are manually inserted by the user and can be adjusted based on the needs and capabilities of the farmer. This formula is applied to both the grow-out and nursery phase. Values for these variables can be seen in Table 2.

$$\textbf{\textit{Length of Crop Production}} = \frac{(\textbf{\textit{Desired Harvest Size}} - \textbf{\textit{Stocking Size}})}{(\textbf{\textit{Growth Rate}}_i)} \tag{1}$$

i = Denotes Year of Production

Equation 2 calculates the total number of full crops harvests the farm produces. Assuming that the farm is operating at 100% capacity year-round, the 'Total Weeks in Operation' would be 52. When the farm is under construction, the production will be less than 100% and the 'Total Weeks in Operation' will be <52. Values for these variables can be found in Table 1.

$$\textbf{\textit{Number of Crops Per Year}} = \frac{(\textbf{\textit{Total Weeks in Operation}})}{(\textbf{\textit{Length of Crop Production}})} \tag{2}$$

Equation 3 calculates the amount of shrimp needed for each crop based on the manual inputs. Each farm scenario assumes 300 shrimp per cubic meter of water for the grow-out phase and 2,100 shrimp per cubic meter of water for the nursery phase. The 'Rearing Tank Volume' for both the grow-out and nursery tanks in this study is 16.1 cubic meters. The 'Water Volume Fill %' for both the grow-out and nursery phase is set at 90 percent. This assumes that the tanks are only ninety percent filled with water. The total number of tanks varies for each farm scenario. Exact parameters for these values can be found in Table 1 and Table 5.

$$\textbf{\textit{Juveniles Needed Per Crop}} = (\textbf{\textit{Stocking Density}})\ \boldsymbol{x}\ (\textbf{\textit{Rearing Tank Volume}})\ \boldsymbol{x}\ (\textbf{\textit{Water Volume Fill}}\ \%)\ \boldsymbol{x}\ (\textbf{\textit{Total Number of Tanks}}_i) \tag{3}$$

i = Denotes Number of Rearing Tanks for Given Scenario

The calculation of annual juveniles is needed (Equation 4) and is a product of Equations 2 and 3. It provides the total amount of shrimp needed based on the farm's capacity and biological data. This formula is applied to both the grow-out and nursey phase.

$$\textit{\textbf{Juveniles Needed Per Year}} = (\textit{\textbf{Juveniles Needed Per Crop}})\ \textit{\textbf{x}}\ (\textit{\textbf{Number of Crops Per Year}}) \tag{4}$$

Equation 5 is applied in calculating the annual production of finished shrimp product for both the grow-out and nursery phase for all three farm scenarios. The desired harvest size for the grow-out phase is 22g and for the nursery phase it is 1.0g.

$$\textit{\textbf{Annual Farm Production}} = (\textit{\textbf{Juveniles Needed per Year}}_i)\ \textit{\textbf{x}}\ (\textit{\textbf{Survival Rate}}_i)\ \textit{\textbf{x}}\ (\textit{\textbf{Desired Harvest Size}}) \tag{5}$$

i = Denotes Year of Production

Equation 6 is a summation calculating how much total shrimp the farm produces at both the grow-out and nursery phases. This was done over the ten years of production.

$$\textit{\textbf{Total Farm Production}} = \sum_{i=1}^{10} \textit{\textbf{Annual Farm Production}}_{\mathbf{i}} \tag{6}$$

i = Annual farm production for the Year

Equation 7 is the calculation for annual salt usage. The grow-out and nursery phases of each farm scenario is exchanging 100% of its water every sixth crop. This involves a complete reapplication of salt to the system every other year of production. The model assumes that 50 pounds of supplemental salt per tank is added in the years that do not require a full water exchange. The supplemental salt is to account for minor adjustments in water and salinity levels.

(7)

$$\boldsymbol{Annual\ Salt\ Usage} = (\boldsymbol{Added\ Salt}_{\mathrm{i}})\ \boldsymbol{x}\ (\boldsymbol{Rearing\ Tank\ Volume})$$
$$\boldsymbol{x}\ (\boldsymbol{Water\ Volume\ Fill}\ \%)\ \boldsymbol{x}\ (\boldsymbol{Total\ Number\ of\ Tanks}_{\mathrm{j}})$$

i = For the grow-out phase - the amount of salt needed to attain 15 parts per thousand (ppt) of salinity per cubic meter of water. For the nursery phase – the amount of salt needed to attain 30 ppt of salinity. This model assumes that it would take 40 pounds of salt per cubic meter of water to attain 15 ppt of salinity and 80 pounds of salt to attain 30 ppt of salinity.

j = Number of Rearing Tanks for Given Scenario

Equation 8 calculates total salt cost taking into consideration the usage of both the nursery and grow-out phases. Exact costs for salt are listed in Table 6.

(8)

$$\boldsymbol{Total\ Salt\ Cost} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{10}} (\boldsymbol{Salt\ Price\ \ x\ \ Annual\ Salt\ Usage}_{\mathrm{i}})$$

i = Denotes Year of Production

Electricity is calculated on a per tank basis (Equation 9). The data for electricity usage varies widely among RAS shrimp farmers due to differences in electrical components. Several RAS shrimp farmers have other forms of enterprise on their property and maintain a single electricity bill. Without an itemized electricity bill, it is difficult for many farmers to provide an accurate assessment on how much monthly electricity their RAS shrimp farm uses. The exact costs for electricity are listed in Table 7.

(9)

$$\boldsymbol{Annual\ Electricity\ Usage} = (\boldsymbol{Monthly\ Kilowatt\ Hours\ Per\ Tank})$$
$$\boldsymbol{x}\ (\boldsymbol{Total\ Number\ of\ Tanks})\ \boldsymbol{x}\ (\boldsymbol{12})$$

The product of ‘Annual Electricity Usage’ and the ‘Price per Kilowatt Hour’ yields the annual cost of electricity (Equation 10). The summation of this product across ten years of production is the ‘Total Electricity Cost.’

$$\boldsymbol{Total\ Electricity\ Cost} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{10}} (\boldsymbol{Price\ Per\ Kilowat\ Hour}_{\mathrm{i}})\ \boldsymbol{x}\ (\boldsymbol{Annual\ Electricity\ Usage}_{\boldsymbol{i}}) \tag{10}$$

i = Denotes Year of Production

Equation 11 calculates ‘Total Gross Receipts’ which is the product of ‘Annual Farm Production’ and the ‘Annual Selling Price’. The summation of this product across ten years of production is the ‘Total Gross Receipts’ for the farm. The inputs parameters for ‘Annual Selling Price’ are listed in Table 8.

$$\boldsymbol{Total\ Gross\ Receipts} = \sum_{\substack{\boldsymbol{i=1}\\ \boldsymbol{j=1}}}^{\boldsymbol{10}} (\boldsymbol{Annual\ Farm\ Production}_{\boldsymbol{i}})\ \boldsymbol{x}\ (\boldsymbol{Annual\ Selling\ Price}_{\mathrm{j}}) \tag{11}$$

i = Annual Farm Production in Year of Production

j = Annual Selling Price in Year of Production

The taxable income for each farm considering the aggregated costs and depreciation expense per the 150% MACRS depreciation schedule is presented in Equation 12.

$$\begin{aligned} &\boldsymbol{Annual\ Reportable\ Income} \\ &\quad = (\boldsymbol{Annual\ Gross\ Receipts}_{\boldsymbol{i}}) - (\boldsymbol{Annual\ Costs}_{\boldsymbol{i}} \\ &\quad + \boldsymbol{Annual\ Depreciation\ Expense}_{\boldsymbol{i}}) \end{aligned} \tag{12}$$

i = Denotes Year of Production

‘Annual Income Taxes’ is calculated as the product of ‘Annual Reportable Income’ and the ‘Corporate Tax rate’ in Equation 13. All farm scenarios were taxed the IRS flat corporate tax rate of 21 percent.

$$\textit{Annual Income Taxes} = (\textit{Annual Reportable Income})\ x\ (\textit{Corporate Tax Rate}) \tag{13}$$

'Annual Income Taxes' is then subtracted from 'Annual Reportable Income' (Equation 14).

$$\textit{Annual Net Income} = (\textit{Annual Reportable Income}) - (\textit{Annual Income Taxes}) \tag{14}$$

Adding 'Annual Depreciation Expense' back to the 'Annual Net Income' generates the farm's 'Annual Net Cash Flow' (Equation 15).

$$\textit{Annual Net Cash Flow} = (\textit{Annual Net Income}) + (\textit{Annual Depreciation Expense}) \tag{15}$$

The farm's Net Present Value (NPV) detailed in Equation 16, takes into consideration the time vale of money. A positive NPV signifies a worthwhile investment in that the projected earnings will exceed the overall costs, while a negative NPV shows that the projected earnings will not exceed the costs. Table 9 shows the input parameters for the discount rate.

$$\textit{Farm Net Present Value} = \sum_{t=1}^{10} \left[\frac{\textit{Annual Net Cash Flow}_t}{(1+i)^t}\right] - \textit{Initial Investment} \tag{16}$$

t = The Year of Production

i = The Discount Rate

3.3 Modifications to Existing Model

Several modifications were made to the model's framework. This was done to ensure thorough analysis and to accommodate for developments in RAS shrimp management practices.

A Modified Accelerated Cost Recovery System (MACRS) 150% depreciation schedule of assets was added in accordance with the Farmer's Tax Guide (U.S. Department of the Treasury, 2019b). Vehicles and buildings were depreciated on a 10-year schedule while the remaining physical assets were depreciated on a 5-year schedule. The calculated depreciation of assets was then used to compute discounted cash-flows and the NPV of the operation.

Added salt was included as a variable input in the model. The original model assumed that the facility is located adjacent to the ocean and added salt is not needed. Per the data collection, the salt level in each farm scenario was kept at 15 ppt (parts per thousand) for the grow-out facility and 30 ppt for the nursery facility. To attain a level of 15 ppt, 40 lbs. of salt per cubic meter of water is required, while 80 lbs. per cubic meter is needed to attain a salinity level of 30 ppt. Every tank is filled to 90% water volume capacity and all the water is drained, refilled, and salted every six crops or every other year. Fifty lbs. of supplementary salt per tank is added in the years that the full water exchange does not occur.

The modeled farm is in the Midwestern U.S. where the winter season can be severe. *L. Vannamei* is a warm water species and requires a water temperature of 23-30 degrees Celsius to grow properly (Bisesi, 2007). Maintaining an indoor air temperature slightly below the farm's water temperature can reduce condensation and possible mold issues, but it is not common practice for farmers to monitor indoor temperature (Ray, 2019). To ensure the facility can maintain year-round production in the colder months, insulation was added as an additional start-up cost at $2.15 per square foot of warehouse space.

Annual maintenance of farm machinery and infrastructure is estimated at 5% of the initial cost. Certain items such as the rearing tanks are assumed to be replaced every five years.

3.4 Stochastic Variables

The original model assumes deterministic values for its inputs and generates a ten-year production schedule and financial performance measures based on those deterministic inputs. The key input stochastic variables for this analysis are:

- Survival Percentage
- Weekly Growth Rate
- PL Cost
- Electricity Costs
- Selling Price

Each variable is given an independent stochastic input for each year of production in the model. This in turn derives yearly production and financial metrics associated with the parameter input for that given year. These modifications were included to account for greater variation associated with the costs, production, and financial performance of RAS shrimp farms on a year-to-year basis.

The Monte Carlo Method (MCM) has been widely used for a wide array of economics, finance, physics, and operations research (Kroese et al., 2014). The goal of MCM is to predict with greater certainty, the likelihood of a certain event or outcome. Once a model's variables are designated stochastic and their appropriate distribution selected, MCM will generate a random number within each distribution and store it; this is one iteration. Hundreds or thousands of these iterations will create an aggregate of values in the form of a distribution. For this project each simulation was run 1000 times.

The @Risk software is used in this study and depending on the scope and goals of the project, it can be a powerful tool in measuring risk and deriving statistical inferences from a wide variety of deterministic, stochastic, and output variables. For stochastic variables, the user has the option to select an array of distributions based on the scenario being modeled. Once the distribution shape and inputs are selected, @Risk will then create a probability density function (PDF) of the stochastic variable. For deterministic variables, the user will need to input the static values. @Risk also has the option of designating output variables which are derived from both the deterministic and stochastic variables in the model. Using MCM Simulation, @Risk will then take a value of the PDF for each stochastic variable depending on the shape of the distribution selected and store them in a histogram figure for further analysis. Correlations between all variables, both deterministic and stochastic, were assumed to be zero.

The triangular distribution is a continuous probability distribution that relies on three inputs of worst-case, most likely, and best-case. It employs geometry to derive its PDF by using the middle value (the most likely) as its peak, while the upper value (maximum) and lower value (minimum) form the outer bounds. Its cumulative density function is that of an ‘S curve’. The triangular distribution is often employed in project management or financial planning where limited or speculative data is only available.

Figure 6 illustrates the triangular distribution’s PDF with the following parameters:

- Minimum Value (a = 1)
- Most Likely Value (c = 6)
- Maximum Value (b = 9)

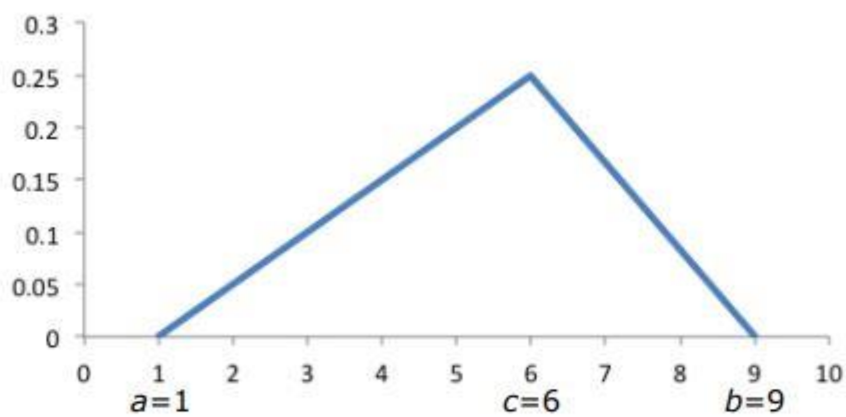

Figure 6 - Graphic Illustration of Triangular Distribution PDF

Source: (Petty and Dye, 2013)

$$f(x) = \begin{cases} 0, & x < a \\ \dfrac{2(x-a)}{(b-a)(c-a)}, & a \le x \le c \\ \dfrac{2(b-x)}{(b-a)(b-c)}, & c \le x \le b \\ 0, & x > b \end{cases}$$

Figure 7 - Mathematical Computation for the Triangular Distribution's PDF

Source: (Petty and Dye, 2013)

3.5 Farm Scenarios

Three different RAS farm scenarios were tested in this study using both the original framework of the Hansen-Posadas bioeconomic model and the modifications. They include 8-tank system, 16-tank system, and 24-tank system. There were several assumptions regarding the model's framework. Land was not included as a capital cost. It is also assumed that each scenario has a consistent supply of PLs to stock the nursery. Another assumption is that all the shrimp produced is sold at the price for that given year. All simulations are done independently of each other and will have no effects on other variables.

3.6 Data Collection

Data for this project came from both research and commercial sources. Six RAS shrimp farmers from the Midwest provided data and various biological parameters such as survival, variable costs, capital costs, and selling prices. For the designated stochastic variables within the model, the participating farms were asked to provide a range of values in the form of "best case", "worst case", and "most likely" in order to mirror the necessary inputs for the distributions. Research data, provided by Kentucky State University's Aquaculture Research Center (KSUARC), was used in places where commercial data was lacking. Energy costs were collected from empirical averages, while variable costs including feed, PLs, and salt were derived from KSUARC.

KSUARC conducted a series of experiments analyzing the performance of LCSMs on the growth, survival, and overall health of *L. vannamei*. The composition of the LCSM can be found in Parmenter et al., (2009). There were four trials of each mixture. Tanks were randomly selected, as the shrimp were grown to the size of 22g. The LCSM was mixed with the industry standard commercial instant sea salt (ISS) at varying intervals:

- 100% LCSM
- 75% LCSM, 25% ISS
- 50% LCSM, 50% ISS
- 25% LCSM, 75% ISS
- 100% ISS

The study conducted in this paper focuses on the cost of LCSMs and the effect they have on overall profitability. It assumes that the shrimp's biological performance is not affected by the adoption of LCSMs.

3.6.1 Variables, Parameters and Distributions

Table 1 presents the biological input parameters for grow-out scenarios for all three RAS farm scenarios. The data from this table was drawn from both the KSUARC and commercial farmers. The 'Stocking Size' is the size of the shrimp when it enters the grow-out stage, while the 'Stocking Density' is the amount of shrimp per cubic meter of water volume in each grow-out tank. The 'Desired Harvest Size' of 22 grams, is the size the shrimp will be grown to. This amounts to roughly 20-21 shrimp per pound. The 'Gross Feed Conversion' is the amount of feed it takes to generate one pound of biomass. For this study, it was assumed that it would take 1.4 pounds of feed to generate 1 pound of biomass. The 'Shut Down Period' is the time it takes to prepare in between crops. The 'Start-Up Period' refers to the amount of time it takes the farmer to construct and begin operations. For this study it was assumed to be six months or 180 days. The 'Rate of Capacity Usage Year 1' calculates how much of the total farm's production capacity is being used. The six-month start-up period is half a year, so the capacity usage is close to fifty percent. After this start-up period in year one, it is implied that the farm is operating year-round at 100% capacity which explains the inputs for the last two variables in Table 1.

Table 1 - Selection of Biological Parameter Values for Grow-Out Scenarios

Variables	**Units**	**8-Tank**	**16-Tank**	**24-Tank**
Stocking Size	grams	1	1	1
Stocking Density	PL/m3	300	300	300
Desired Harvest Size	grams	22	22	22
Gross Feed Conversion	#	1.4	1.4	1.4
Shut Down Period	Day/Crop	2	2	2
Start-Up Period	Days	180	180	180
Rate of Capacity Usage Year 1	%	51	51	51
Rate of Capacity Usage Year 2-10	%	100	100	100
Number of Weeks in Operation	Weeks/Year	52	52	52

Table 2 presents the stochastic variables and their distribution for the three grow-out scenarios. Using the Monte Carlo Method, @Risk centers the probability mass around the 'Likeliest' input. For example, in Table 2 under 'Survival year 3-10, 90% of the random numbers drawn will lie between 53.54% and 70.67%. 'Survival Year 1' (40, 40, 45) and 'Survival Year 2' (45, 45, 60) are lower than that of 'Survival Year 3-10' (50, 60, 75). By shifting the 'most likely' parameter downwards, the probability that lower numbers are drawn during MCM simulation increases. This was implemented to ensure a lower number is drawn in those two years, representing a learning curve in acquiring necessary managerial skills and practices in the initial years. By year three, the survival rate % distribution will remain constant to signify an acquisition of necessary managerial skills. The minimum and likeliest values for survival are identical in both distribution of 'Survival Year 1' and 'Survival Year 2' (Table 2).

The gathering of growth and survival rate data was very challenging. Commercial farmers either lacked data entirely or gave rough estimates. Data provided by researchers was larger and more nuanced, however the biological data gathered from these experiments were conducted by aquaculture experts in a lab-controlled, non-commercial setting. The goal of this study was to use the data provided by both parties and construct a more conservative estimate of each distribution's parameters.

Table 2 - Selection of Distribution and Stochastic Biological Parameter Values for Grow-Out Scenarios

Variables	**Units**	**Distribution**	**Range**	**8 Tank**	**16 Tank**	**24 Tank**
Survival Year 1	%	Triangular	Minimum	40	40	40
			Likeliest	40	40	40
			Maximum	45	45	45
Survival Year 2	%	Triangular	Minimum	45	45	45
			Likeliest	45	45	45
			Maximum	60	60	60
Survival Year 3-10	%	Triangular	Minimum	50	50	50
			Likeliest	60	60	60
			Maximum	75	75	75
Growth Rate Year 1	g/week	Triangular	Minimum	1.1	1.1	1.1
			Likeliest	1.2	1.2	1.2
			Maximum	1.3	1.3	1.3
Growth Rate Year 2	g/week	Triangular	Minimum	1.2	1.2	1.2
			Likeliest	1.3	1.3	1.3
			Maximum	1.4	1.4	1.4
Growth Rate Year 3-10	g/week	Triangular	Minimum	1.3	1.3	1.3
			Likeliest	1.4	1.4	1.4
			Maximum	1.5	1.5	1.5

Table 3 presents the biological input parameters for the nursery stage for all three RAS farm scenarios. The data was also collected from the KSUARC in addition to the commercial farmers polled in this study. The justification and clarification of these variables is the same as the description of Table 1.

After speaking with farmers and researchers it was clear that the survival rates for the nursery phase of RAS production were significantly higher than that of the grow-out stage. Due to their smaller size, the weekly growth rates were smaller as well. The justification and clarification for the variables in Table 4 can be found in the description of Table 2.

Table 3 - Selection of Biological Parameter Values for Nursery Scenarios

Variables	Units	8-Tank	16-Tank	24-Tank
Stocking Size	grams	0.004	0.004	0.004
Stocking Density	PL/m3	2,100	2,100	2,100
Desired Harvest Size	grams	1	1	1
Gross Feed Conversion	#	1.25	1.25	1.25
Shut Down Period	Day/Crop	2	2	2
Rate of Capacity Usage Year 1	%	51	51	51
Rate of Capacity Usage Year 2-10	%	100	100	100
Number of Weeks in Operation	Weeks/Year	52	52	52

Table 4 - Selection of Distribution and Stochastic Biological Parameter Values for Nursery Scenarios

Variables	Units	Distribution	Range	8-Tank	16-Tank	24-Tank
Survival Year 1	%	Triangular	Minimum	70	70	70
			Likeliest	70	70	70
			Maximum	80	80	80
Survival Year 2	%	Triangular	Minimum	75	75	75
			Likeliest	75	75	75
			Maximum	85	85	85
Survival Year 3-10	%	Triangular	Minimum	80	80	80
			Likeliest	85	85	85
			Maximum	95	95	95
Growth Rate Year 1	g/week	Triangular	Minimum	0.175	0.175	0.175
			Likeliest	0.175	0.175	0.175
			Maximum	0.18	0.18	0.18
Growth Rate Year 2	g/week	Triangular	Minimum	0.18	0.18	0.18
			Likeliest	0.18	0.18	0.18
			Maximum	0.185	0.185	0.185
Growth Rate Year 3-10	g/week	Triangular	Minimum	0.185	0.185	0.185
			Likeliest	0.190	0.190	0.190
			Maximum	0.20	0.20	0.20

Table 5 presents the facility and investments for each farm scenario. All the commercial farmers that participated in this study had systems containing 8-10 total tanks. The 16-tank and 24-tank scenario’s 'Total Start-Up Costs’ were scaled based on the costs provided from these farmers. Farm set-ups vary significantly in this industry as do the total costs. It is the goal of this study to emphasize more conservative estimates of all the model’s inputs.

Table 5 - Selection of Facility and Infrastructure Values for Both Grow-Out and Nursery Scenarios

Variables	**Units**	**8-Tank**	**16-Tank**	**24-Tank**
Rearing Tank Volume	m3	16.1	16.1	16.1
Water Volume	%	90	90	90
Total Rearing Houses	#	1	1	1
Total Grow-Out Tanks	#	7	14	21
Total Nursery Tanks	#	1	2	3
Total Structural Space	Square ft.	2,800	5,600	8,400
Total Start-Up Cost	$	$65,000	$115,000	$165,000

Table 6 details the usage parameters used in this study. All costs and usage rates were derived from commercial farmers and research facilities. PL10 Cost Year 1-10’ refers to the shrimp being purchased from hatcheries that are then stocked in the nursery tanks. Like the biological parameters in Table 2, there are ten individual cell inputs for PL10 costs, and each year of production is linked to that specific input. This model assumes a consistent supply of PLs, but since these hatcheries are vulnerable to risk themselves, price variation on a yearly basis was built into each scenario within this study. ‘Capital Costs’ inputs were obtained from banking professionals in addition to commercial farmers who had sought financing. ‘Electricity Usage’ was obtained from commercial farmers. Usage varied amongst the farmers who provided electricity data for this study. Some farmers have diversified farming operations that are all connected to a single meter. Calculating an accurate range of electricity usage for these operations was challenging as some farmers declined to provide data.

Table 6 - Selection of Distribution and Stochastic Cost and Usage Parameter Values for Both Grow-Out and Nursery Scenarios

Variables	Units[1]	Distribution	Range	8 Tank	16 Tank	24 Tank
PL10 Cost Year 1-10	$/1000	Triangular	Minimum	29.00	29.00	29.00
			Likeliest	30.00	30.00	30.00
			Maximum	40.00	40.00	40.00
Grow-Out Salt Cost	$/Ton	Triangular	Minimum	800	800	800
			Likeliest	1,500	1,500	1,500
			Maximum	2,300	2,300	2,300
Nursery Salt Cost	$/Ton	Triangular	Minimum	800	800	800
			Likeliest	1,500	1,500	1,500
			Maximum	2,300	2,300	2,300
Grow-Out Feed Cost	$/Ton	Triangular	Minimum	1,400	1,400	1,400
			Likeliest	1,450	1,450	1,450
			Maximum	1,500	1,500	1,500
Nursery Feed Cost	$/Ton	Triangular	Minimum	6,000	6,000	6,000
			Likeliest	7,000	7,000	7,000
			Maximum	8,000	8,000	8,000
Capital Cost	%	Triangular	Minimum	5	5	5
			Likeliest	6	6	6
			Maximum	8	8	8
Electricity Usage	Kwh/Tank /Month	Triangular	Minimum	500	500	500
			Likeliest	700	700	700
			Maximum	900	900	900

1 $/Ton refers to English Tons

The distribution of salt costs presented in Table 6 assumes that the most likely value will be around $1,500/ton, implying that a mixture of both LCSM and ISS salts is used in the initial, baseline simulation. Salt usage was calculated based on commercial farming data. It was assumed that the grow-out phase for each scenario had salt concentration at roughly 15 ppt (parts per thousand) salinity while the nursery stage was 30 ppt. Salinity levels of 15 and 30 ppt could be attained by adding 40 pounds and 80 pounds respectively of salt per cubic meter of water. These inputs are catalogued in Table 7.

Table 7 - Selection of Cost and Input Parameter Values for Farm Scenarios

Variables	Units	8-Tank	16-Tank	24-Tank
Added Salt Per m3 – Grow Out (15ppt)	lbs.	40	40	40
Added Salt Per m3 – Nursery (30 ppt)	lbs.	80	80	80
Electricity Cost – Year 1*	$/kwh	$0.110	0.110	0.110
Electricity Cost – Year 2*	$/kwh	$0.111	0.111	0.111
Electricity Cost – Year 3*	$/kwh	$0.112	0.112	0.112
Electricity Cost – Year 4*	$/kwh	$0.113	0.113	0.113
Electricity Cost – Year 5*	$/kwh	$0.114	0.114	0.114
Electricity Cost – Year 6*	$/kwh	$0.115	0.115	0.115
Electricity Cost – Year 7*	$/kwh	$0.116	0.116	0.116
Electricity Cost – Year 8*	$/kwh	$0.117	0.117	0.117
Electricity Cost – Year 9*	$/kwh	$0.118	0.118	0.118
Electricity Cost – Year 10*	$/kwh	$0.119	0.119	0.119
Telephone Expense	$/week	$25.00	$25.00	$25.00
Gasoline Cost	$/gal	$2.25	$2.25	$2.25
Propane Cost	$/gal	$2.50	$2.50	$2.50
Hauling Cost	$/lb	$0.10	$0.10	$0.10
Annual Labor (Fixed)	$	$10,000	$20,000	$30,000
Capital Outlay Index	%	100%	100%	100%
Annual Liability Insurance	$	$600	$900	$1,200
Corporate Tax Rate	%	21%	21%	21%

***** The electricity costs assume a $0.001 increase per year (U.S. Department of Energy, 2019b)

This study assumed that each farm scenario exchanged their water every six crops and added fresh salt as well. In the years that water is not exchanged entirely, it was assumed that each scenario added roughly 50 pounds of salt per tank to account for variance in water loss. For the nursery phase, the salinity was roughly 30 ppt due to the nursery shrimp requiring a salinity level resembling full strength seawater. The same water exchange schedule as the grow-out stage was applied to the nursery stage. More salt was needed per tank in the nursery stage due to the higher ppt, but with far fewer tanks.

According to historical prices provided by the U.S. Department of Energy, electricity prices increase around $0.001 per kilowatt hour every year (U.S. Department of Energy, 2019b). Gasoline and propane costs were taken from national averages provided by the EIA for 'Heating Oil and Propane' and 'Petroleum & Other Liquids' (U.S. Department of Energy, 2019c, 2019a). 'Telephone Expense" was calculated to be around $100 per month or $25 per week. 'Hauling Cost' implied a fixed rate for additional hired labor to harvest and/or haul finished product. 'Annual Labor' costs were assumed to be fixed in this case, and the justification for these values was based on the commercial data provided. It is also assumed that the increase in scale of production equates to an equal increase in fixed labor costs. ‘Capital Outlay Index’ assumes that each scenario is financed entirely. ‘Annual Liability Insurance’ was calculated to be 1% of the total investment. ‘Corporate Tax Rate’ was derived from the Internal Revenue Service’s flat corporate rate of 21% (U.S. Department of the Treasury, 2019a).

The distribution of shrimp selling prices was determined from data collected from commercial farmers (Table 8). All shrimp sold in each scenario are head-on, whole shrimp. Like the biological parameters in Table 2 and the ‘PL10 Costs’ in Table 6, there are ten individual cell inputs for shrimp prices, and each year of production is linked to that specific input. This was implemented to assume future market price fluctuations for RAS-grown shrimp.

Table 8 - Distribution Parameter of the Selling Price of Shrimp

Variables	Units	Distribution	Range	8 Tank	16 Tank	24 Tank
Price Year 1-10	$/lb	Triangular	Minimum	$16.00	$16.00	$16.00
			Likeliest	$18.00	$18.00	$18.00
			Maximum	$20.00	$20.00	$20.00

Table 8 calculates the break-even prices for each farm scenario. To calculate the break-even price, all stochastic variables were made deterministic by using the middle or ‘most likely’ value and the total costs (Variable Costs + Fixed Costs + Depreciation) were then divided by the ‘Total Units Sold’ (pounds of shrimp). All the variables in Table 8 were totaled over a ten-year production schedule.

The annual number of crops or ‘turns’ is an important factor when planning livestock production. Using the same deterministic model, the number of annual crops for each scenario was 3.40 when operating at 100% capacity. The model uses the data inputs from Tables 1-3 to generate the length of each crop and divides it by the number of weeks in operation. To operate at 100% capacity, each farm scenario is in operation 52 weeks per year. Since each scenario uses the same biological inputs, the number of crops remains the same. However, the size of the crops does vary between each scenario considerably since each scenario’s production is governed by the number of tanks.

Table 9 – Statistics and Break-Even Prices for Each Farm Scenario – Deterministic Models

Variables	Units	8-Tank	16-Tank	24-Tank
Selling Price	$/lb	$18.00	$18.00	$18.00
Total Units Sold	lbs	27,442	54,884	82,327
Total Revenue	$	$493,963.88	$987,927.77	$1,481,891.65
Total Depreciation	$	$71,307	$127,648.16	$183,988.44
Total Variable Costs	$	$221,918.06	$409,434.35	$595,335.30
Total Fixed Costs	$	$152,447.19	$281,632.16	$414,796.03
Total Costs	$	$445,673.13	$818,714.67	$1,194,119.77
Profit	$	$48,290.75	$169,213.09	$287,771.88
Break-Even Price	$/lb	$16.24	$14.92	$14.50

3.8 Key Output Variable (KOV)

Net Present Value (NPV) - The NPV takes into consideration the time value of money. A positive NPV signifies a worthwhile investment in that the projected earnings will exceed the overall costs, while a negative NPV signifies the opposite in that the project will result in a loss. The computation for NPV is listed in Equation 16.

Table 10 details the stochastic distribution of the discount rate used to calculate each scenario's NPV. The discount rate is the return one can expect if the start-up costs for each scenario were put towards an alternative investment. When assessing agricultural projects, the distribution's values in Table 10 are appropriate.

Table 10 - Selection of Distribution and Stochastic Discount Rates for NPV Calculation

Variables	Units	Distribution	Range	8 Tank	16 Tank	24 Tank
Discount Rate	%	Triangular	Minimum	7%	7%	7%
			Likeliest	9%	9%	9%
			Maximum	11%	11%	11%

3.9 Stress and Sensitivity Analysis

@Risk has an assortment of tools to incorporate sensitivity analyses. One of these tools is the tornado graph. The tornado graph ranks the input variable's effect on the KOV mean and provides the user with a visual and numerical representation of that effect. After running MCM method through @Risk, tornado figures for the NPV key output variables were gathered for each farm scenario simulation. The largest contributors to mean variance were then selected for subsequent stress analysis.

Under @Risk's 'Advanced Analyses' tool, users can alter or stress the KOV's mean by drawing from a specific range on any input variable's distribution. A separate simulation of 1000 iterations were then run for each stressed input variable, generating separate KOV data. All simulations were done independent of each other, ceteris paribus. Using @Risk's 'Summary' tool, the KOV data generated by the stressed input variables were then compared to the original KOV data.

3.10 Stress Test on Salt Ratios – Background and Computations

To examine the effect of implementing the different salt ratios (both high cost and low-cost), a separate series of stress analyses were conducted on the input variable controlling for salt costs, with NPV again being the key output variable. Using data from KSUARC's salt mixture experiments in addition to data gathered from commercial RAS farmers, the triangular distribution inputs for salt costs were meant to represent the different ratios of salt a farmer can employ. As stated before, the Baseline NPV scenario implies that a 50:50 ratio of LCSM and ISS is used.

The distribution of the key input variable for salt costs is presented in Figure 7. About 90% of the salt cost distribution values within the Baseline NPV Scenario, were between $1,029 and $2,055. A table of probability deciles for this variable is presented in Table 11. All farm scenarios will draw from the same distribution.

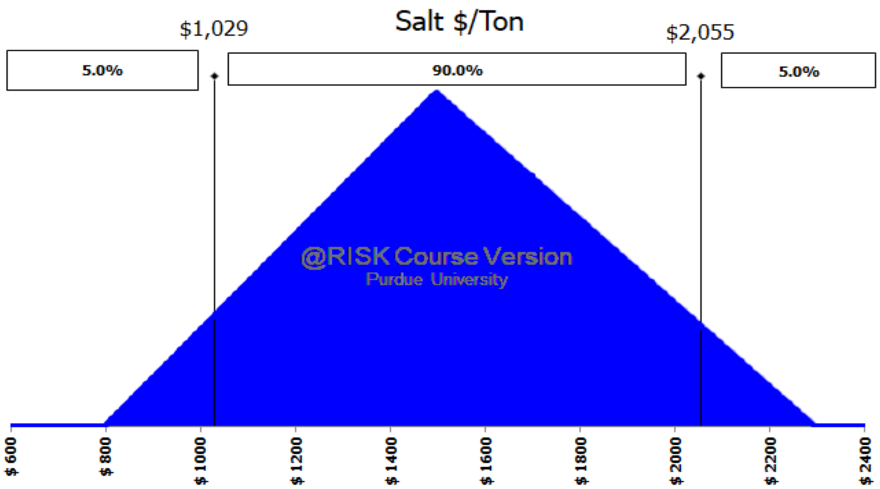

Figure 7 - Triangular PDF of Salt Costs for 8-Tank, 16-Tank, and 24-Tank Systems

Table 11 - Probability Deciles of the Triangular Distribution for Salt $/Ton

Probability Decile	Units	Low	High
10%	$	$1,487	$1,565
20%	$	$1,448	$1,607
30%	$	$1,406	$1,652
40%	$	$1,361	$1,700
50%	$	$1,312	$1,752
60%	$	$1,258	$1,810
70%	$	$1,197	$1,876
80%	$	$1,124	$1,954
90%	$	$1,029	$2,055
100%	$	$800	$2,300

CHAPTER 4 – RESULTS

MCM simulation was run on three different farm scenarios with the key output variable being Net Present Value. The following tables display the results for each farm scenario's MCM simulation.

4.1 8-Tank Scenario Results

After 1000 iterations using both the model's deterministic values and stochastic key variable inputs, the results aggregated the values in the form of a histogram (Figure 8). The probability ranges and summary statistics are presented in Tables 12-14 The values take on the shape of a normal distribution. The probability decile ranges are catalogued in Table 12.

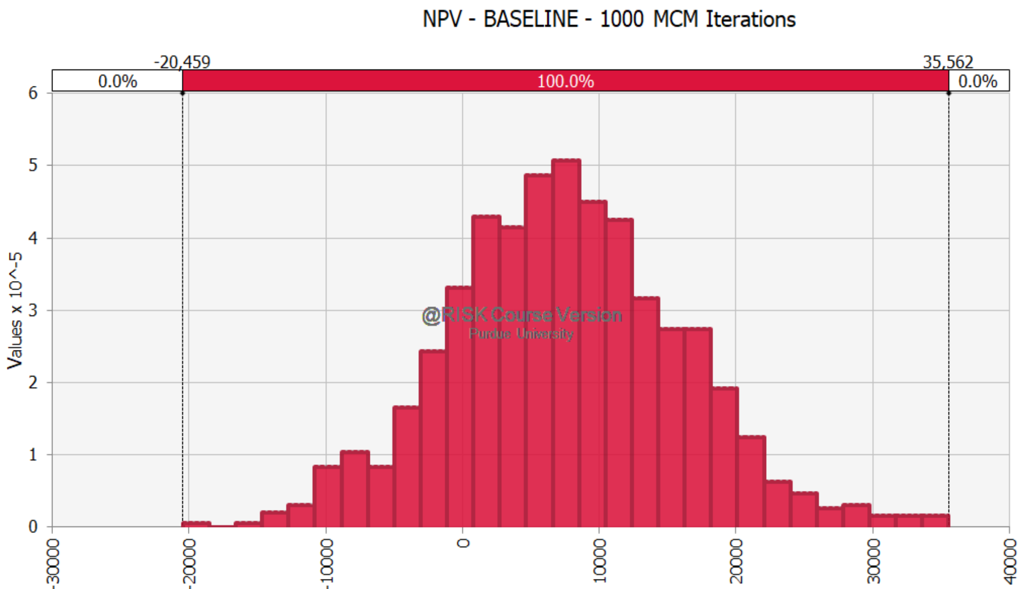

Figure 8 - Aggregated NPVs for 8-Tank System

Table 12 - Probability Deciles of Aggregated NPVs for the 8-Tank System

Probability Decile	Units	Low	High
10%	$	$6,272	$8,356
20%	$	$5,335	$9,376
30%	$	$4,070	$10,500
40%	$	$2,946	$11,493
50%	$	$1,756	$13,079
60%	$	$582	$14,667
70%	$	-$963	$16,469
80%	$	-$2,911	$18,290
90%	$	-$6,307	$21,359
100%	$	-$20,459	$35,562

The probability deciles were obtained from the various stochastic variables and their assigned distribution values, in addition to the deterministic variables provided for the 8-tank RAS system. The results in Table 12 are the range of NPV values and the probability of their occurrence. For example, there is a 10% chance that the NPV of an 8-tank RAS system will fall within the range of $6,272 and $8,356. As the probability decile decreases, the range decreases as well.

In Table 13, the summary statistics generated show that the mean, median, and mode resemble a normal distribution. The expected value for kurtosis within a normal distribution is 3.00 while the skewness is 0.00. The aggregated NPV values for the 8-tank system display slightly higher kurtosis at 3.23. With a skewness of 0.15 the aggregated NPV values in Figure 8 are slightly skewed to the right.

Table 13 - Summary Statistics for the 8-Tank System

Summary Statistic	Units	Value
Minimum	$	-$19,195.36
Maximum	$	$36,247.32
Mean	$	$7,530.59
Mode	$	$6,946.64
Median	$	$7,458.83
Standard Deviation	$	$8,576.07
Skewness	#	0.14
Kurtosis	#	3.14

4.1.1 Stress Analyses on Important Variables: 8-Tank Scenario

From the sensitivity analyses, the grow-out survival percentage, electricity usage, discount rate, selling price, and salt costs have the biggest effect on NPV mean variance. To simulate an additional year of learning on the farmer's behalf, grow-out survival percentage for the third year of production was drawn from the lower five percent of the distribution. To simulate a higher alternative investment, the discount rate will be higher – only pulling from the upper five percent of the initial distribution. A drop in the selling price is shown by drawing from the lower five percent of the variable controlling for price. The stress tests for these three variables support downside risk analysis, while the stress test for electricity usage (kwh per year) supports upside risk analysis, simulating a reduction in overall electricity usage. The summary statistics for each stress test is presented in Table 14.

Table 14 - Summary Statistics of Aggregated NPVs From Stress Tests on Four Additional Variables for the 8-Tank System

Summary Statistic	Baseline Scenario	Grow-Out Survival Year 3 (0-5%)	Kwh Per Year (0-5%)	Discount Rate (95-100%)	Selling Price (0-5%)
Min	$-19,195.36	$-25,563.67	$-9,657.57	$-20,974.31	$-35,365.25
Max	$36,247.32	$29,921.06	$42,489.28	$25,037.58	$11,469.06
Mean	$7,530.59	$2,929.01	$14,135.44	$2,003.74	$-11,085.79
Mode	$6,946.64	$1,552.68	$11,074.20	$-1,535.12	$-8,563.49
Median	$7,458.83	$2,816.10	$14,096.44	$1,845.73	$-10,944.67
Std Dev	$8,576.07	$8,143.00	$8,149.31	$7,439.89	$7,305.01
Skewness	0.14	0.13	0.12	0.10	0.01
Kurtosis	3.14	3.17	3.09	3.01	2.97
(NPV<0)	17.40%	36.20%	3%	40.30%	93.2%

Pulling from only the lower bound (0-5%) of the distribution for 'Survival Year 3', resulted in a negative effect on the aggregated NPVs for the 8-tank system by decreasing the minimum value and increasing the probability of a loss. The stress conducted on the Discount Rate had a similar effect by increasing the probability of a loss and the minimum value, while decreasing the remaining summary statistics.

The stress test on the electricity usage, where only values from the lower bound (0-5%) of the distribution were drawn, resulted in a positive effect on aggregated NPVs as both the minimum value and probability of a loss were decreased while the remaining summary statistics increased. The last column of Table 14 showed the effect on NPV if the values for annual selling price were pulled from the lower 5% of each distribution. It had a significant effect by increasing the likelihood of a loss to over 93% and reducing the mean NPV. All simulations were conducted independently of each other and the results of each stress test assume ceteris paribus.

Using the data generated from each stress test scenario in Table 14, the probability of a net loss can be found on the bottom row. The first column corresponds to the Baseline Scenario and yielded a 17.4% likelihood of a net loss. The second simulation, which drew from the lower 5% of the variable controlling for grow out survival % in year 3 of production, increased the probability of a net loss to 36.2%. The third simulation, which drew from the lower 5% of the variable controlling for electricity usage in kwh/year, decreased the probability of a net loss to 3%. The fourth simulation, which drew from the upper 5% of the variable controlling for discount rate %, increased the probability of a net loss to 40.3%.

4.1.2 Stress Tests on Salt Ratios: 8-Tank Scenario

To simulate the implementation of various salt ratios, a series of stress tests were conducted on the variable controlling for salt costs. It is assumed that the 'Baseline Scenario' uses roughly a 50/50 mix of ISS and LCSM salt mixture. The ratio of ISS and LCSM mixtures and the portion of the variable's distribution are as follows:

- 100% ISS solution: The cost was drawn only from the upper 5% of the distribution (Lower Bound: $2,055 & Upper Bound: $2,300)
- 75% LCSM, 25% ISS mix: The cost was drawn only from the upper 75-95% of the initial salt cost distribution (Lower Bound: $1,752 & Upper Bound: $2,055)
- 25% LCSM, 75% ISS mix: The cost was drawn only from the lower 5-25% of the initial salt cost distribution (Lower Bound: $1,029 & Upper Bound: $1,312)
- 100% LCSM solution: The cost was drawn only from the lower 0-5% of the initial salt cost distribution (Lower Bound: $800 & Upper Bound: $1,029.13)

Table 15 shows the results from each stress test. The four columns to the right of the 'Baseline Scenario" represent four separate scenarios in which the different salt ratios are implemented. The percentage values located in the parenthesis represent the portion of the distribution the values are drawn from.

Table 15 - Summary Statistics of Aggregated NPVs From Stress Tests on Salt Costs for the 8-Tank System

Summary Statistic	Baseline Scenario	100% ISS (95-100%)	75% ISS 25% LCSM (75-95%)	25% ISS 75% LCSM (5-25%)	100% LCSM (0-5%)
Min	$-19,195.36	$-24,089.73	$-17,783,14	$-19,656.46	$-14,070.79
Max	$36,247.32	$34,900.52	$37,359.28	$37,464.28	$39,927.09
Mean	$7,530.59	$3,764.30	$5,840.15	$10,486.43	$11,760.59
Mode	$6,946.64	$3,133.30	$3,173.81	$8,695.01	$11,621.77
Median	$7,458.83	$3,775.09	$5,384.19	$10,294.53	$11,363.35
Std Dev	$8,576.07	$8,453.74	$8,685.11	$8,753.85	$8,523.95
(NPV<0)	17.40%	34.0%	24.50%	11.0%	7.40%

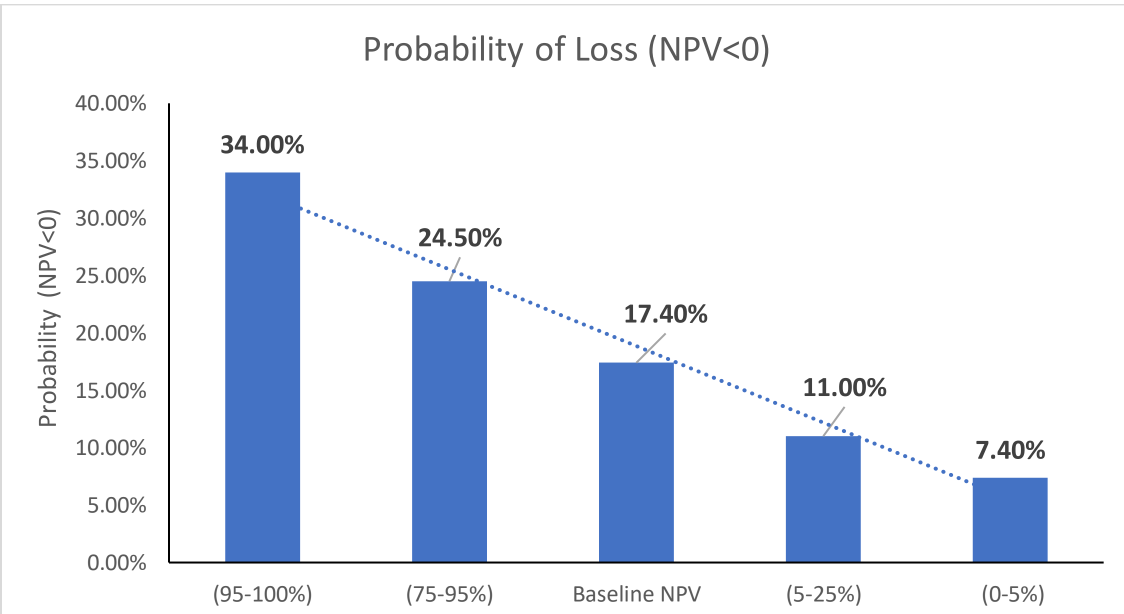

Figure 9 - Probability of a Loss for Each Salt Cost Stress Test on 8-Tank System

Adoption of 100% ISS and the 100% LCSM mixtures had the most significant impact on the probability of a net loss. From Figure 9, the adoption of 100% ISS increased the probability of a net loss from 17.40% to 34.0% while the adoption of 100% LCSM reduced the probability of a net loss from 17.4% to 7.40%. A mix ratio of 75% ISS and 25% LCSM increased the likelihood of a net loss from 17.40% to 24.50%, while a ratio of 25% ISS and 75% LCSM decreased the likelihood of a net loss from 17.40% to 11%.

Using the data generated from each stress test scenario, the probability of a net loss (NPV<0) is shown in Figure 9**.** The middle point corresponds to the Baseline Scenario (50/50 mixture of ISS and LCSM) and yielded a 17.4% likelihood of a net loss. The other columns show the probability of a net loss (NPV<0) associated with the adoption the various ISS/LCSM salt ratios. The data shows that the implementation of LCSMs in RAS farming can reduce the likelihood of a net loss assuming ceteris paribus regarding the other stochastic variables within the model.

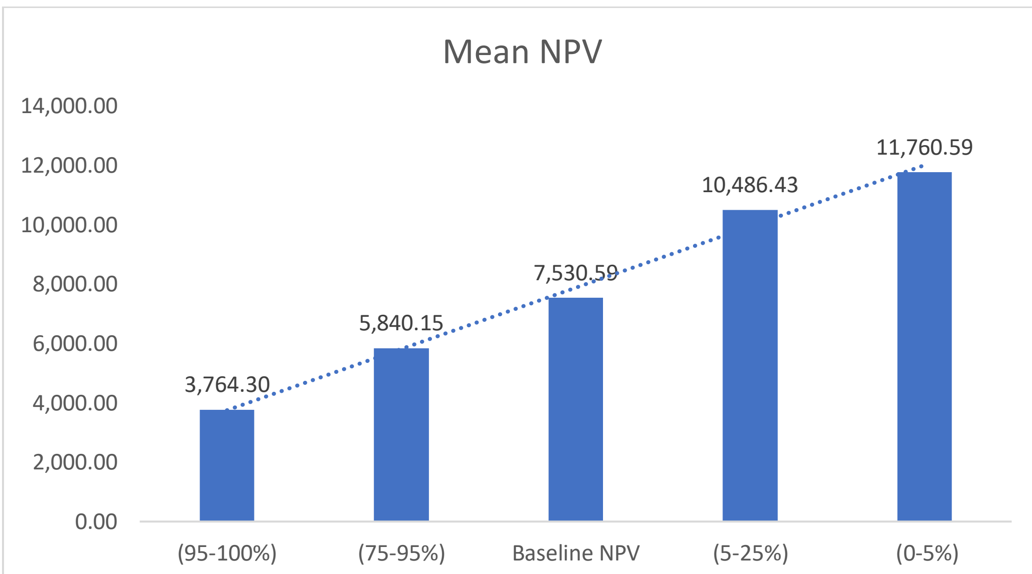

Figure 10 – Effect on Mean NPV for Each Salt Cost Stress Test on 8-Tank System

Adoption of 100% ISS and the 100% LCSM mixtures had the most significant impact on the average NPV as well. From Figure 10, the adoption of 100% ISS decreased the average NPV from $7,530.59 to $3,764.30 while the adoption of 100% LCSM increased the average NPV from $7,530.59 to $11,760.59. A mix ratio of 75% ISS and 25% LCSM decreased the average NPV from $7,530.59 to $5,840.15, while a ratio of 25% ISS and 75% LCSM increased the average NPV from $7,530.59 to $10.486.43. The results also show a 212.4% increase in the average NPV between the 100% ISS solution and a 100% LCSM solution.

4.2 16-Tank Scenario Results

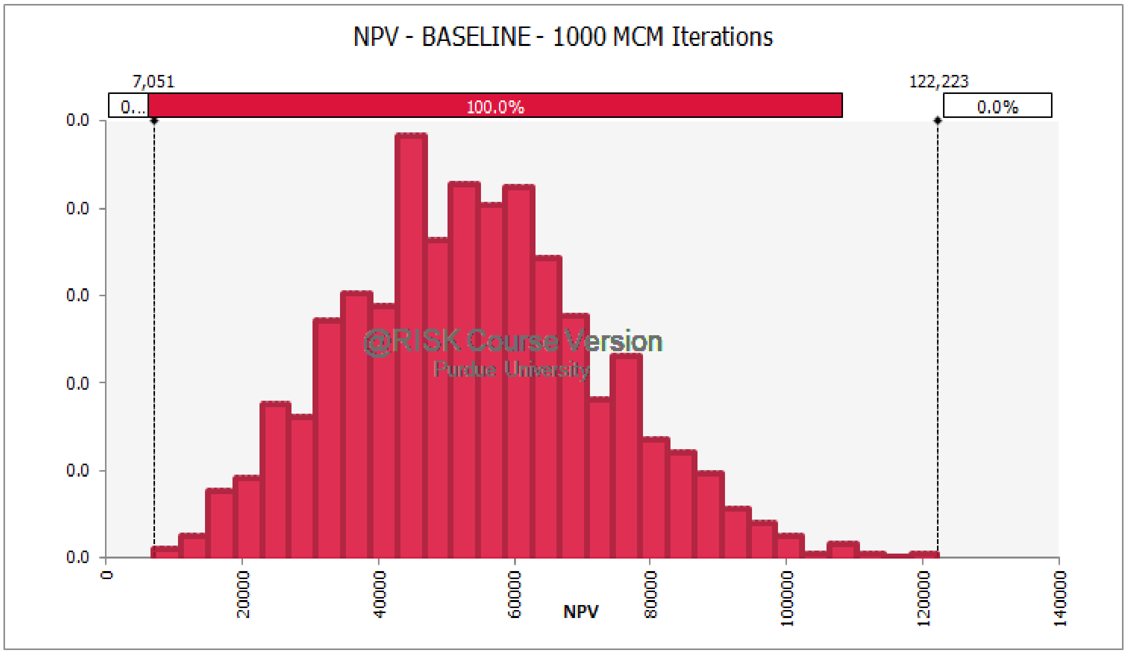

Figure 11 – Aggregated NPVs for 16-Tank System

After 1000 iterations of MCM, @Risk software aggregated the resulting NPVs in the form in Figure 20. The probability decile ranges are catalogued in Table 15.

The probability deciles were obtained from the various stochastic variables and their assigned distribution values, in addition to the deterministic variables provided for the 16-tank RAS system. The results in Table 16 are interpreted as the range of NPV values and the probability of their occurrence. Of the 1000 iterations, none of the NPVs was found to be negative.

Table 16 - Probability Deciles of Aggregated NPVs for the 16-Tank System

Probability Decile	Units	Low	High
10%	$	$51,037	$55,466
20%	$	$48,418	$57,843
30%	$	$45,778	$60,651
40%	$	$43,865	$63,043
50%	$	$41,182	$65,897
60%	$	$37,096	$69,075
70%	$	$34,199	$73,516
80%	$	$29,969	$78,229
90%	$	$24,182	$86,019
100%	$	$7,051	$122,223

Table 17 - Summary Statistics for the 16-Tank System

Summary Statistic	Units	Value
Minimum	$	$7,051
Maximum	$	$122,223
Mean	$	$53,872
Median	$	$52,954
Mode	$	$52,338
Standard Deviation	$	$18,649
Skewness	#	0.25
Kurtosis	#	2.88

In Table 17, the summary statistics show that the mean, median, and mode resemble a normal distribution. The aggregated NPV values for the 16-tank system display a lower kurtosis and higher skewness compared to the aggregated values for the 8-tank system. The distribution of aggregated values for the 16-tank system is skewed more to the right than the 8-tank system.

4.2.1 Stress Analyses on Important Variables: 16-Tank Scenario

The same variables used in the 8-tank scenario were incorporated in the stress analysis on NPV for the 16 Tank scenario. The summary statistics in comparison to the Baseline 16-tank system, are presented in Table 18.

Table 18 - Summary Statistics of Aggregated NPVs From Stress Tests on Four Additional Variables for the 16-Tank System

Summary Statistic	Baseline Scenario	Grow-Out Survival Year 3 (0-5%)	Kwh Per Year (0-5%)	Discount Rate (95-100%)	Selling Price (0-5%)
Min	$7,051	-$1,611	$13,999	-$3,087	$-39,199.84
Max	$122,223	$100,636	$123,699	$90,995	$72,227.34
Mean	$53,872	$44,829	$68,895	$40,782	$13,859.25
Mode	$52,338	$53,538	$60,031	$40,047	$12,879.55
Median	$52,954	$44,394	$68,731	$40,796	$13,425.08
Std Dev	$18,649	$16,847	$17,036	$15,218	$15,841.23
Skewness	0.25	0.11	0.14	-0.013	0.21
Kurtosis	2.88	2.941	2.85	2.85	3.38
(NPV<0)	0.00%	0.30%	0.0%	0.40%	18.0%

Pulling from only the lower bound (0-5%) of the distribution for ‘Grow-Out Survival Year 3,’ had a negative effect on the aggregated NPVs by decreasing the minimum value and increasing the probability of a loss. The stress test conducted on the ‘Discount Rate’ had a similar effect by slightly increasing the probability of a loss and decreasing the minimum value, while decreasing the remaining summary statistics. The stress test on the electricity usage had a positive effect on aggregated NPVs. The final column shows the effect a lower selling price has on NPV. The likelihood of a loss increases to 18% and the mean NPV is reduced significantly. All simulations were conducted independently of each other.

4.2.2 Stress Tests on Salt Ratios: 16-Tank Scenario

To incorporate the adoption of different salt ratios, the same salt cost stress analyses conducted on the 8-tank system were conducted on the 16-tank scenario.

Table 19 shows the results from each stress test. The four columns to the right of the ‘Baseline Scenario” represent four separate scenarios in which the different salt ratios are implemented. The ‘Baseline Scenario’ assumes roughly a 50/50 ratio of ISS and LCSM mixtures. The percentage values located in the parenthesis represent the portion of the distribution the values are drawn from.

Table 19 - Summary Statistics of Aggregated NPVs From Stress Tests on Four Additional Variables for the 16-Tank System

Summary Statistic	Baseline Scenario	100% ISS (95-100%)	75% ISS 25% LCSM (75-95%)	25% ISS 75% LCSM (5-25%)	100% LCSM (0-5%)
Min	$7,050.89	$-12,181.83	$-9,112.31	$-707.43	$6,798.15
Max	$122,223.35	$112,677.37	$112,049.77	$132,272.27	$112,969.84
Mean	$53,872.32	$45,566.78	$49,574.16	$58,020.31	$60,352.29
Mode	$52,338.07	$52,386.38	$48,693.73	$49,358.52	$53,890.93
Median	$52,954.27	$44,445.83	$49,012.75	$58,038.80	$59,609.23
Std Dev	$18,649.51	$18,311.71	$17,558.87	$18,919.41	$18,181.05
(NPV<0)	0.00%	<0.10%	<0.10%	<0.10%	0.00%

Since the probability of a net loss was 0.00% in the Baseline scenario, the mean NPV was chosen as a performance indicator for the 16-tank scenario. It is assumed that the Baseline scenario uses close to a 50-50 ISS/LCSM ratio. Further implementation of LCSM mixtures increases the average NPV.

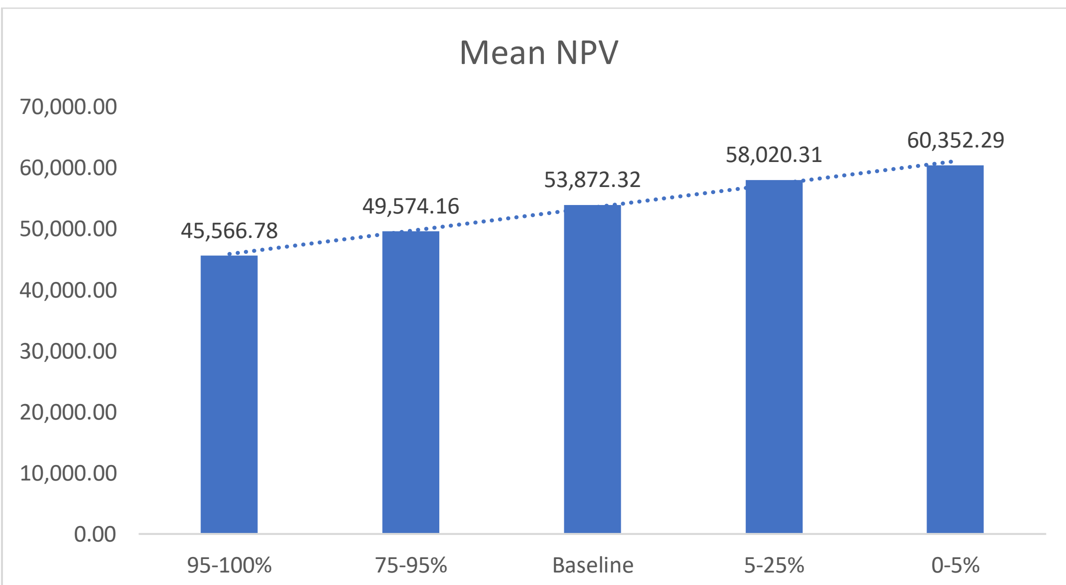

Figure 12 - Effect on Mean NPV from Salt Cost Stress Tests on 16-Tank System

4.3 24-Tank Scenario Results

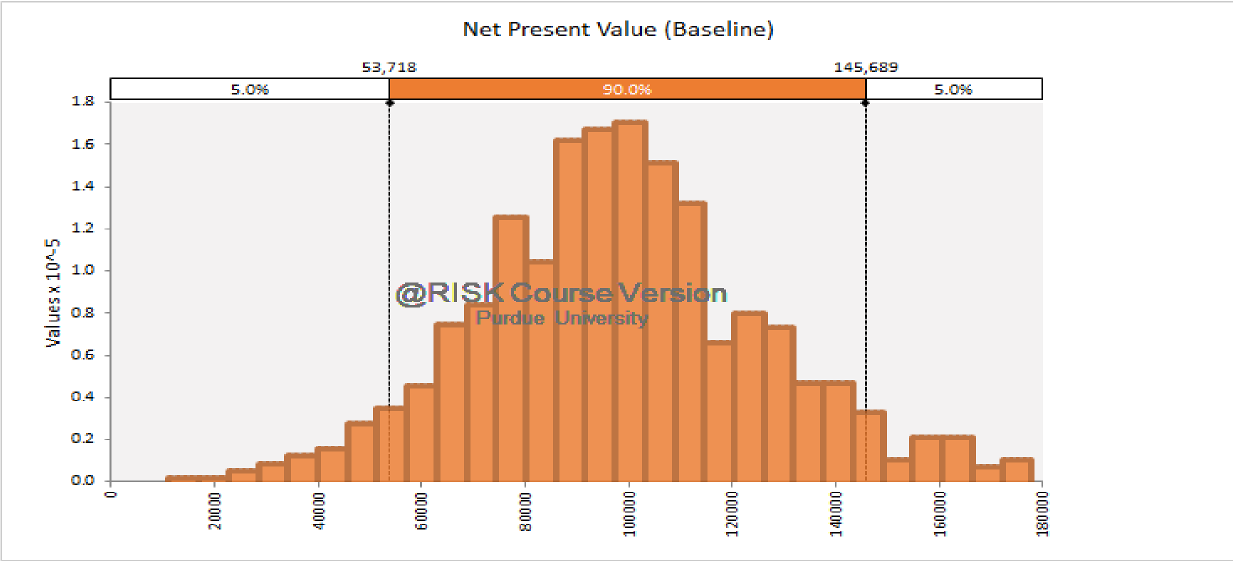

Figure 13 - Aggregated NPVs for 24-Tank System

The resulting NPVs from this tank system is shown in Figure 13. The probability decile ranges are catalogued in Table 20. After 1000 MCM iterations, there were zero scenarios where the NPV was negative.

Table 20 - Probability Deciles of Aggregated NPVs for the 24-Tank System

Probability Decile	Units	Low	High
10%	$	$94,148	$100,164
20%	$	$91,182	$103,188
30%	$	$88,766	$106,490
40%	$	$84,940	$110,235
50%	$	$80,038	$114,258
60%	$	$76,602	$120,417
70%	$	$71,661	$126,386
80%	$	$64,655	$134,251
90%	$	$53,718	$145,689
100%	$	$11,193	$177,836

Table 21 - Summary Statistics for the 24-Tank System

Summary Statistic	Units	Value
Minimum	$	$11,193
Maximum	$	$177,836
Mean	$	$98,284
Median	$	$97,360
Mode	$	$91,115
Standard Deviation	$	$27,413
Skewness	#	0.16
Kurtosis	#	3.21

In Table 21, the summary statistics show that the mean, median, and mode also resemble a normal distribution. The 24-tank system displayed kurtosis and skewness that resembled that of the 8-tank system.

4.3.1 Stress Analyses on Important Variables: 24-Tank Scenario

The same variables were incorporated in the stress analysis on NPV for the 24 Tank scenario. The summary statistics in comparison to the Baseline, are presented in Table 22.

Table 22 - Summary Statistics of Aggregated NPVs From Stress Tests on Four Additional Variables for the 24-Tank System

Summary Statistic	Baseline Scenario	Grow Out Survival Year 3 (0-5%)	Kwh Per Year (0-5%)	Discount Rate (95-100%)	Selling Price (0-5%)
Minimum	$11,193	-$1,283.95	$44,014.60	$9,304.50	-$32,439.35
Maximum	$177,836	$173,150	$192,609.42	$155,102.87	$120,969.85
Mean	$98,284	$83,997	$119,434.33	$75,888.02	$38,042.86
Mode	$91,115	$87,959	$121,068.84	$70,117.91	$37,370.50
Median	$97,360	$84,584	$118,955.41	$76,758.12	$37,454.43
Std Dev	$27,413	$26,6412	$25,873.20	$23,483.44	$23,214.53
Skewness	0.16	0.0191	0.1277	-0.0655	0.2155
Kurtosis	3.21	2.80	2.7091	2.8552	3.0031
(NPV<0)	0.00%	<0.10%	0.00%	0.00%	5.00%

Pulling from only the lower bound (0-5%) of the distribution for ‘Grow-Out Survival Year 3’ had a negative effect on the aggregated NPVs by decreasing the minimum value. The stress test conducted on the 'Discount Rate' decreased the minimum value, while decreasing the remaining summary statistics. The stress test on the electricity usage had a positive effect on aggregated NPVs. 'Selling Price (0-5%)' had a negative effect on all summary statistics and increased the probability of a loss to 5.00%.

4.3.2 Stress Tests on Salt Ratios: 24-Tank Scenario

To simulate the adoption of the different salt ratios, the same salt cost stress analyses were conducted on the 24-tank scenario. The results of each simulation are summarized in Table 23.

Table 23 - Summary Statistics of Aggregated NPVs From Stress Tests on Salt Costs for the 24-Tank System

Summary Statistic	**Baseline Scenario**	**100% ISS (95-100%)**	**75% ISS 25% LCSM (75-95%)**	**25% ISS 75% LCSM (5-25%)**	**100% LCSM (0-5%)**
Min	$11,193	$6,720	$9,604	$21,713	$17,911
Max	$177,836	$175,537	$175,520	$189,550	$210,114
Mean	$98,284	$85,394	$89,274	$105,135	$108,569
Mode	$97,360	$77,651	$91,099	$106,436	$112,974
Median	$91,115	$84,985	$88,525	$104,202	$107,327
Std Dev	$27,413	$27,595	$27,189	$27,260	$28,019
(NPV<0)	0.00%	0.00%	0.00%	0.00%	0.00%

Table 23 shows the results from each stress test. The four columns to the right of the 'Baseline Scenario" represent four separate scenarios in which the different salt ratios are implemented. The 'Baseline Scenario' assumes roughly a 50/50 ratio of ISS and LCSM mixtures. The percentage values located in the parenthesis represent the portion of the distribution the values are drawn from.

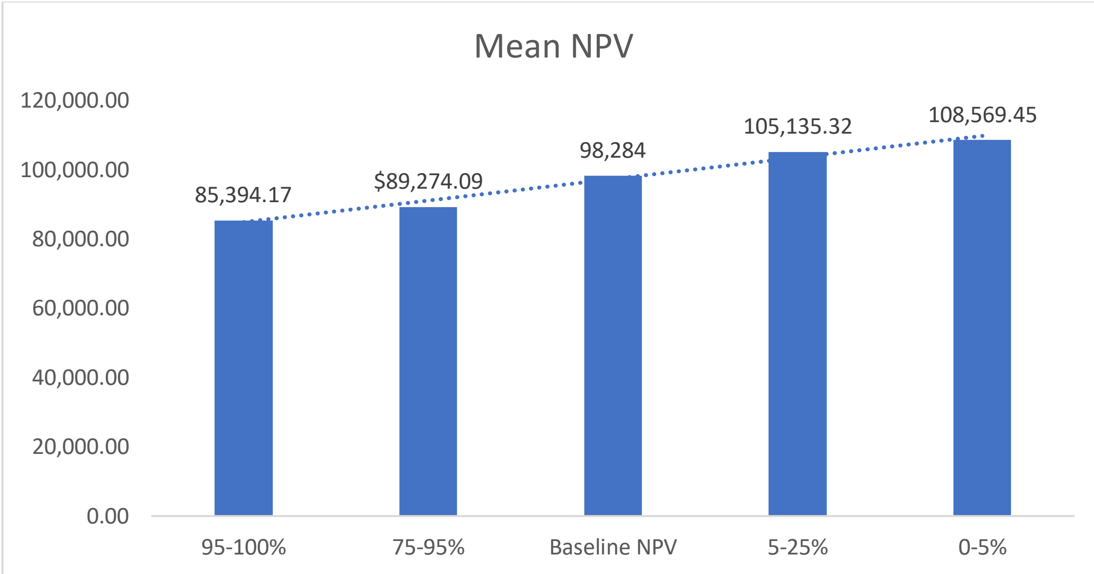

Figure 14 - Effect on Mean NPV from Salt Cost Stress Tests on 24-Tank System

Since the probability of a net loss was 0.00% in the Baseline scenario, the mean NPV was chosen as a performance indicator for the 24-tank scenario. It is assumed that the Baseline scenario uses close to a 50-50 ISS/LCSM ratio. Figure 14 shows that further implementation of LCSMs increases the average NPV.

CHAPTER 5 - DISCUSSION OF RESULTS

The 8-tank scenario's initial probability of success was lower than that of the 16-tank and 24-tank scenarios and was far more sensitive to the stressed variables. The baseline scenario yielded a probability of a net loss of 17.4%. The first stress analysis on the grow-out survival percentage in year 3 of production doubled the probability of a net loss to 36%. This scenario was highly sensitive to electricity usage and the discount rate as well. The probability changes the net loss to 3% for lower electricity usage and to over 40% for a higher discount rate. For the 8-tank scenario to be feasible, a decrease in yearly kwh of electricity and high survival rates are needed. The 8-tank scenario's sensitivity to the discount rate shows that an alternative investment of similar resources and capital could prove to be a better decision. If the LCSM has no effect on the survival, growth, or overall performance of the shrimp, increasing the LCSM ratio can have a positive effect on the financial performance of the 8-tank scenario and could mitigate some internal risks.

The 16-tank scenario's initial probability of success was higher than the 8-tank system and was less sensitive to the stressed variables. The baseline scenario yielded a 0.0% probability of a net loss. The first stress analysis on the grow-out survival percentage in year 3 of production increased the probability of a net loss to 0.4%. This scenario was sensitive to electricity usage and the discount rate as well, but from a downside risk perspective, the probability of a loss was not affected. The data from these simulations show that the increase in production can greatly mitigate some of the internal risks of the smaller system. An increase in LCSM for the 16-tank system also had a positive effect on mean NPV.

The 24-tank scenario's initial probability of success was higher than the 16-tank. The stress test on electricity, grow out survival in production year 3, and the discount rate affected the NPV the least of all three scenarios. The baseline scenario yielded a 0.0% probability of a net loss. The first stress analysis on the grow-out survival percentage in year 3 of production did not change the probability of a net loss. This scenario was sensitive to electricity usage and the discount rate as well by reducing mean NPV, but the probability of a loss was not affected. Stressing the price of shrimp had a significant effect by increasing the probability of a loss to 5% and reducing the mean NPV by 61%. The farmers interviewed in this study receive a price premium by selling directly to consumers and restaurants, but this market has limited sales volume, causing farmers to explore other wholesale distribution channels where offered prices will be lower but at higher sales volume. An increase in LCSM for the 24-tank system also had a positive effect on mean NPV, but the increase was less significant in comparison to the 8-tank and 16-tank systems.

The results from this study show that an increase in production scale lowers internal risks and increases profitability. The 8-tank system, given its smaller production capabilities is more vulnerable to fluctuations in certain key variables when compared to larger production systems. The use of LCSMs for each system has a positive effect, especially in the 8-tank system. For RAS ventures to succeed, standardizing RAS technology and increased research in both aquaculture economics and management will be paramount to their success.

CHAPTER 6 - SUMMARY AND CONCLUSION

As the world population continues to increase, new technologies aimed at increasing efficiencies in our global food system will continue to be a topic of great discussion. Recirculating Aquaculture Systems (RAS) have been touted as one of the technologies that can be used for seafood production to help meet the increased global protein demand due to their year-round production capabilities, location flexibility, and smaller environmental impact in comparison to wild-caught seafood and large-scale pond aquaculture. The purpose of this paper is to provide an economic analysis of RAS shrimp farming and quantify the risks involved.

Results from the analyses performed in this paper suggest that scaling production will decrease the risks involved in terms of costs. More production and increased revenue can offset the various risks associated with many of the variable inputs assuming there is a secured market and high prices. This of course depends on maintaining high prices in the future. If the price were to drop as more producers enter the market, this would cause some profitability challenges. There is lack of data and many of the assumptions embedded in this study including labor, selling prices, land values, electricity usage, etc. could prove to be inaccurate when scaling RAS shrimp operations. None of the scenarios include the opportunity cost of the owner/operator's time either.

Small changes in certain input factors and biological parameters can have a significant effect on the farm's profitability. Scaling up can mitigate some of these risks, but for small-scale farmers, the results of this study show that there are risks involved and obtaining price premiums are necessary to make this a sound investment. Due to the technological and biological complexities of biofloc RAS, proper management becomes critical as well to prevent catastrophic failures. Potential farmers can get into shrimp farming as a diversified farming operation in addition to other existing agricultural ventures to minimize risks in their overall farming portfolio.

The adoption of LCSMs can have a positive effect on mitigating risk in these systems, particularly smaller operations like the 8-tank system. However, further research is needed to fully assess their effect on the biological performance of shrimp production – particularly in a full-scale commercial setting.

CHAPTER 7 - LIMITATIONS AND FURTHER RESEARCH

RAS shrimp farming is a very small industry in the U.S. and conducting any sort of academic study on it can be very challenging for several reasons. The first is lack of commercial data. With very few farmers, there is a challenge in locating them and gathering substantive data. Many of the farmers interviewed in this study had other farming ventures beside their RAS shrimp farms which made estimating certain costs or usage rates challenging. Since this is such a nascent industry, there is no standard method to RAS shrimp farming. There are debates over water exchange levels, the use of clearwater vs biofloc, various engineering setups and whether any of them really improve farm performance. It is not uncommon to see farms experiment on their own and adopt certain technologies or managerial methods as they seem fit. It was the goal of this study to gather data from farmers and aquaculture researchers in the Midwest that are implementing similar methods and practices. As RAS technology improves and more farmers enter the industry, managerial methods and technology could be standardized as in other mature, more established livestock industries. The increase in farms and information will provide future researchers with more data and allow for more substantive analysis.

RAS shrimp farmers in the U.S. are vulnerable to a series of external risks that this study does not capture. For example, RAS shrimp farmers need consistent, quality juveniles from hatcheries. This model assumes that this supply is consistent, but unfortunately that is not always the case. Hatcheries themselves are subject to many of the same risks as the farms they supply including disease outbreaks, high operating costs, and weather-related incidents. The permanent or even temporary closure of one of the hatcheries could spell doom for many of the RAS shrimp farms. Also, the success of these farms is predicated on them selling in a niche market and selling their product for a high price. If demand for high-priced, RAS-grown shrimp were to go down, the industry would suffer. A study that uses this model's framework but implements a series of discrete, binomial distributions to simulate the occurrence of various external events is necessary.

There continues to be opportunity within this model to better analyze the risks and opportunities of RAS shrimp farming. A linear programming model between certain key input variables could be very useful in establishing thresholds and relaying that information to current and future stakeholders. Using the same approach in this study regarding stress and sensitivity analyses of key input variables, would be beneficial to examine their effect on other key output variables. This model's framework could also be applied to clearwater RAS shrimp farms or even finfish operations. Further studies on the correlations between key input variables such as stocking density, growth rates, survival, etc. will also be useful. Additional studies examining other financial performance measures such as the farm's Internal Rate of Return (IRR) would be beneficial in further assessing economic viability. The intention of this study to show how sensitive each system is to changes in key input variables. Whether one scenario is superior to another depends on a multitude of factors not captured in this paper.

Despite these limitations, this study is one of the more thoughtful, analytical studies of the internal risks and performance of domestic RAS shrimp farms ever conducted.

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