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The value of mono-gender production in Atlantic salmon farming

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ABSTRACT

Efforts to enhance production efficiency in the aquaculture industry are imperative to ensure its sustainable growth. The aim of this study is to investigate whether the usage of mono-gender smolt in Atlantic salmon farming can increase value of operations for salmon producers. Mono-male and mono-female smolt exhibit distinct biological characteristics, with males demonstrating accelerated growth rates, albeit being more exposed to the risk of sexual maturation, while females display reduced susceptibility to such maturation risks and grow at a comparatively slower pace. Despite the potential benefits of optimizing mono-gender smolt production, the economic viability of employing such strategies within a risk-reward framework has not been studied before In this paper, we compare the production efficiency and the operational risk of different compositions of mono-gender to the mixed-gender production plans. The study is performed by simulating multi-location productions of mono-gender and mixed-gender salmon based on actual production data. In all scenarios investigated, mono-gender production provides solutions with higher expected value and lower operational risk. The increased value of mono-gender production is driven by improved flexibility in the production planning and better utilisation of gender-specific biological properties, which outweighs the higher cost of mono-gender smolt. The optimal composition of genders is dependent on the quality downgrade factor, the cost of smolt and the risk preferences of the producer. Nevertheless, higher shares of all-female deployments are generally found to provide the best risk/reward profile. While providing valuable insights, the study's focus on gender-specific traits leaves out the consideration of market price uncertainty, suggesting a potential avenue for future research.

1. Introduction

Aquaculture industry plays an important role in satisfying growing demand for marine proteins worldwide. Nevertheless, it faces several challenges for further growth. The expansion of the industry has led to undesirable environmental challenges, such as increased pollution of the sea bed, higher prevalence of diseases and sea lice, and negative impacts on the genetics and spawning grounds of the wild salmon (Arechavala-Lopez et al., 2022). This creates significant operational risks for the producer, leading to substantial profit losses (Abolofia et al., 2017). Overcoming the industry challenges and ensuring further growth, while at the same time reducing the operational risk, is therefore dependent on improving the production efficiency.

This paper investigates mono-gender smolt as a potential measure to increase the efficiency in Atlantic salmon production. More specifically, we evaluate the effects the introduction of mono-gender smolt has on the value of production and the operational risk based on a case study in Norway. We do this by incorporating mono-gender smolt as an operational choice in a multi-location production simulation, where we account for gender-specific growth, mortality and sexual maturation rates, as well as differentiated smolt costs. The primary hypothesis of our study is that the use of mono-gender smolt in production yields economic and operational advantages, driven by gender-specific biological properties. The output of our simulation model is the accumulated value and associated operational risk related to a given production plan. By comparing the outputs for mono-gender and mixed-gender plans, we assess whether mono-gender production can uncover additional value for salmon producers and investigate its value drivers. Furthermore, we study how mono-gender can be implemented to provide the optimal risk/reward profile of the production.

As the harvested salmon is the only output from Atlantic salmon farming, the value created by the producer is primarily driven by how efficient the salmon is bred from roe to harvest-ready fish. This includes the time the salmon needs to grow to the desired size and the degree of the produced batches that complete the entire production cycle (Sandvold, 2016). Selective breeding of salmon genetics has been an

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important determinant for the improved production efficiency, as it has led to higher growth and survival rates, increased quality of the fish and a lower share of early sexual maturation (Næve et al., 2022). The introduction of different genetic profiles potentially enables the farmer to increase the flexibility in the planning process, which in turn can increase the utilisation of available resources and the efficiency of the production. Furthermore, increasing the number of operational choices enables the production to reflect the producers' risk preferences better.

In order to assess how mono-gender smolt can reduce the operational risk, we focus on two risk factors affected by choice of salmon gender: mortality and early sexual maturation. The baseline monthly mortality rate in Atlantic salmon farming is approximately 0.5%, which leads to a substantial loss of biomass in the production (Oliveira et al., 2021). Recent production data has though shown that mono-gender production has been associated with a lower mortality rate than mixed-gender production (Ayllon et al., 2019). Sexual maturation also contributes to an increased production risks as it leads to substantial economic losses for the producer due to the downgrading of fish (Crouse et al., 2022). Moreover, high shares of downgraded fish in the market can contribute to insufficient market supply, leading to even higher differences between the premium quality and the downgraded quality salmon. This happened in Norway during the first half of 2022, where the market experienced historically high price levels and a downgrade factor of approximately 35% (Furuset, 2022). As the maturation process can more easily be controlled with female salmon than male salmon, selective breeding allows for better exploitation of the gender-specific properties by reducing the risk of mortality and quality downgrading in the production, and can hence be favourable for the production output (Ayllon et al., 2019).

While female salmon is associated with a lower risk of early sexual maturation, male salmon has a higher growth rate (Ayllon et al., 2019; Crouse et al., 2022). This leads to a shorter production period, implying a higher frequency of produced batches and consequently an improved expected output from the production. However, as all-male production also is associated with a higher rate of sexual maturation, the gain in value is accompanied by increased operational risk. This reflects the trade-off between risk and expected return in the choice between different production cohorts, where the desired option will depend on the producers' risk preferences. Since Atlantic salmon producers are generally risk-averse, enabling them to match the production to the risk preferences is highly beneficial (Roll, 2019). In our paper, the risk associated with the production is measured by the volatility of the production output.

Despite a sizeable literature on production optimizing under operational risks, few studies focus on the implications of introducing mono-gender smolt in Atlantic salmon farming. However, similar studies have been conducted for aquaculture production of other species. For example, Kumar and Engle (2011) investigates the relative profitability and operational risk related to introducing hybrid fingerlings[1] in catfish production and concludes that the hybrid option has a higher initial cost but at the same time provides lower mortality and greater total yield of the production.

Among the studies on including mono-gender smolt in Atlantic salmon farming are Næss and Patricksson (2019) and Aasen (2021). They develop a two-stage stochastic mixed-integer linear programming models with the objective to maximise expected harvested volume, where the possibility of mono-male salmon in the production is introduced. We contribute to this line of research by investigating how downgrading, gender-specific growth, sexual maturation and mortality rates, differentiated smolt costs and weight differentiated variable prices affect n the economic value and the operational risk of the production.

Our results indicate that the use of mono-gender smolt in Atlantic salmon farming significantly outperforms mixed-gender production. By combining all-male and all-female batches in the production, the increased flexibility and better biomass utilisation enable the producer to achieve higher returns and lower operational risk than by using regular mixed-gender smolt. This finding challenges the current state of the industry and operational practices. We find that the optimal distribution of all-male and all-female batches in the production plan is dependent on the producers' risk preferences and is influenced by the price downgrade factor and the smolt costs. More deployments of all-male batches are favourable in periods with a low downgrade factor. In contrast, all-female deployments are favourable when the downgrade factor is high. Nevertheless, our findings imply that higher shares of all-female provide the most favourable risk/return profiles.

This paper is organised as follows. Section 2 introduces the model and methodology. Section 3 describes the data used in the case study. Section 4 presents results and discussion. Finally, Section 6 concludes.

2. Methodology

2.1. Modelling of underlying factors

In this section, we first present the modelling of growth, sexual maturation and mortality. To differentiate the underlying factors of each gender, a set of cohorts, C, is defined. The set consists of three cohort types: Male (M), Female (F) and Mixed (X). Furthermore, we introduce a set of locations L, consisting of the different production sites.

The Thermal Growth Coefficient-method (TGC) is applied to model the growth of the salmon for each gender cohort C, due to its simplicity and robustness (Aunsmo et al., 2014). We assume that salmon of similar gender in the same batch grow at the same rate. The growth from a time period t to $t+1$ is given by:

$$w_{t+1}^{L,C} = \left(\left(w_t^{L,C} \right)^{\frac{1}{3}} + \frac{TGC_t^C}{1000} \cdot T_t \cdot PL_t^L \right)^3, \tag{1}$$

where $w_t^{L,C}$ represents the weight in grams for a fish of cohort C at location L at time t. TGC_t^C gives the TGC-value for cohort C at time t, while T_t^L and PL_t gives the average seawater temperature at location L and the length in days of the time period starting at t, respectively.

To incorporate the effect of sexual maturation on the quality of produced salmon, each batch is divided between immature fish with superior quality, n^I, and mature fish with downgraded quality, n^M, which are assumed to have similar growth profiles. As maturation only happens during certain times of the year, we introduce the seasonal dummy variable D_t, which equals 1 for the time periods where maturation can occur and 0 otherwise. By denoting the share of salmon in cohort C that goes into maturation in time period t by $g_t^C(z)$, the number of downgraded salmon at location L in time period $t+1$ can be written as $n_{t+1}^{L,C,M} = n_t^{L,C,M} + D_t \cdot n_t^{L,C,I} \cdot g_t^C(z)$..

The maturation rates $g_t^C(z)$ are assumed to follow a log-normal distribution, where z can be interpreted as the share of a salmon batch that matures.[2]

The loss of biomass in a batch over the production time depends on the mortality of the cohort. The quantity of salmon in a batch of cohort C at location L in time period $t+1$ must equal the quantity in time period t multiplied by $\left(1 - m_t^C\right)$, where m_t^C represents the mortality rate for cohort C in time period t, which is assumed to be similar for immature and mature salmon. By combining mortality and maturation in the modelling of the salmon quantity, we get the following expressions for respectively immature and mature salmon:

$$n_{t+1}^{L,C,I} = \left(1 - m_t^C\right) \cdot \left(n_t^{L,C,I} - D_t \cdot n_t^{L,C,I} \cdot g_t^C(z)\right), \tag{2}$$

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[1] Juvenile catfish, equivalent to salmon smolt.

[2] Calculation of the sexual maturation rate $g_t^C(z)$ given a stochastic z-value is discussed in detail in Appendix A.

$$n_{t+1}^{L,C,M} = \left(1 - m_t^C\right)\cdot\left(n_t^{L,C,M} + D_t\cdot n_t^{L,C,I}\cdot g_t^C(z)\right). \tag{3}$$

Combined, the total quantity of salmon is expressed by:

$$n_{t+1}^{L,C} = n_{t+1}^{L,C,I} + n_{t+1}^{L,C,M} \tag{4}$$

Next, we add specific constraints and relevant parameters that capture essential aspects of realistic production. First, we include constraints on the biomass capacity of the production, both on the single sites and at company level. Each production location L is coupled with a production capacity MAB^L. The site capacity is included as a constraint on biomass in the simulated production, given by:

$$n_t^{L,C}\cdot w_t^{L,C} \leq MAB^L \tag{5}$$

Furthermore, the company MAB limit MAB^{COMP} is included as a biomass constraint on the sum of biomass in all of the production locations. This constraint is given by:

$$\sum_L\sum_C n_t^{L,C}\cdot w_t^{L,C} \leq MAB^{COMP} \tag{6}$$

When calculating the value of the production, we use differentiated market prices for each period in the simulated production cycle to incorporate seasonality effects. Price uncertainty is disregarded in the modelling, as this affects both genders equally. The price in time period t depends on the weight class and quality of the salmon:

$$P_t^{C,Q}\left(w_t^{L,C}\right) = TAB_t\left(w_t^{L,C}\right)\cdot\left(1 - DGF_t(Q)\right), \tag{7}$$

where $P^{Q,C}\left(w_t^{L,C}\right)$ is the price of a salmon in cohort C in time period t, with weight $w_t^{L,C}$ and quality Q. The table function $TAB_t\left(w_t^{L,C}\right)$ returns the price (per kg) of the weight class that the salmon of weight w_t belongs to in the time period t, while $DGF_t(Q)$ gives the downgrade factor for salmon of quality Q in time period t. For $Q = I$, DGF equals 0, while for $Q = M$, DGF is dependent of the time period t and varies between 0% and 100%.

Production costs are denoted by S^C and H^C, representing the smolt and harvesting costs. Other costs related to feeding, labour and energy are omitted as they have the same impact on all cohort types.

We also add a constraint on the valid deployment time periods, which modelled by setting V_t^L to 1 if time period t is a valid deploying time period at location L, and to 0 else, so that the following holds:

$$\sum_C s_t^{L,C} \leq V_t^L. \tag{8}$$

In addition, each location can hold at most one batch in each time period. In order to ensure that, we introduce the variable ρ_t^L, which equals 1 if location L holds a batch at time t, and else 0. Then it holds that

$$\rho_{t+1}^L = \rho_t^L + \sum_C s_t^{L,C} - h_t^L. \tag{9}$$

The following two constraints are added to ensure that no batch is deployed before the previous batch on the location is harvested. The first constraint requires that a batch of cohort C in time period t never is set out at location L unless the location is empty, meaning ρ_t^L equals 0. The second constraint makes sure a batch in a location only can be harvested if the given location contains fish.

$$s_t^{L,C} \leq 1 - \rho_t^L, \tag{10}$$

$$h_t^L \leq \rho_t^L. \tag{11}$$

The locations have to be fallowed in between production cycles. To account for this, we introduce the parameter F^L, which describes the number of periods location L has to lie fallow before the release of a new batch.

$$h_t^L + \sum_{F^L}\sum_C s_{t+F^L}^{L,C} \leq 1. \tag{12}$$

We also add constraints on the number of batches that can be set out and harvested in each time period. By denoting the number of batches that the salmon farmer in time period t is able to deploy, S^{CAP}, and harvest, H^{CAP}, we have:

$$\sum_L\sum_C s_t^{L,C} \leq S^{CAP}, \tag{13}$$

$$\sum_L h_t^L \leq H^{CAP}. \tag{14}$$

2.2. Model formulation

The variables representing the decisions of deploying and harvesting a batch of cohort C at location L and time period t are denoted by $s_t^{L,C}$ and h_t^L, respectively. These are combined to obtain the objective function, where the aim is to maximise the expected value of production:

$$\max_{s_t^{L,C},\ h_t^L} \quad \sum_T\sum_L\sum_C\sum_Q\left\{h_t^L\cdot\left(P_t^{C,Q}\left(w_t^{L,C}\right)\cdot w_t^{L,C}\cdot n_t^{L,C,Q} - H^C\right) - s_t^{L,C}\cdot S^C\right\} \tag{15}$$

where:

$$s_t^{L,C} = \begin{cases} 1 & \text{if a batch of cohort } C \text{ at location } L \text{ is set out at time } t \\ 0 & \text{else} \end{cases}, \tag{16}$$

$$h_t^L = \begin{cases} 1 & \text{if a batch at location } L \text{ is harvested at time } t \\ 0 & \text{else} \end{cases}, \tag{17}$$

$$w_{t+1}^{L,C} = \left(\left(w_t^{L,C}\right)^{\frac{1}{3}} + \frac{TGC_t^C}{1000}\cdot T_t^L\cdot PL_t\right)^3, \tag{18}$$

$$n_{t+1}^{L,C,I} = \left(1 - m_t^C\right)\cdot\left(n_t^{L,C,I} - D_t\cdot n_t^{L,C,I}\cdot g_t^C(z)\right), \tag{19}$$

$$n_{t+1}^{L,C,M} = \left(1 - m_t^C\right)\cdot\left(n_t^{L,C,M} + D_t\cdot n_t^{L,C,I}\cdot g_t^C(z)\right), \tag{20}$$

$$n_{t+1}^{L,C} = n_{t+1}^{L,C,I} + n_{t+1}^{L,C,M}, \tag{21}$$

$$n_t^{L,C}\cdot w_t^{L,C} \leq MAB^L, \tag{22}$$

$$\sum_L\sum_C n_t^{L,C}\cdot w_t^{L,C} \leq MAB^{COMP}, \tag{23}$$

$$\sum_C s_t^{L,C} \leq V_t^L, \tag{24}$$

$$\rho_{t+1}^L = \rho_t^L + \sum_C s_t^{L,C} - h_t^L, \tag{25}$$

$$s_t^{L,C} \leq 1 - \rho_t^L, \tag{26}$$

$$h_t^L \leq \rho_t^L, \tag{27}$$

$$h_t^L + \sum_{F^L}\sum_C s_{t+F^L}^{L,C} \leq 1, \tag{28}$$

$$\sum_L\sum_C s_t^{L,C} \leq S^{CAP}, \tag{29}$$

$$\sum_L h_t^L \leq H^{CAP}. \tag{30}$$

The formulation of the discrete stochastic dynamic model contains two decision variables, where each decision must be taken at each time period over the entire production cycle. This includes decisions of when and in which location to deploy and harvest salmon, and which gender to choose in the deployment. The large number of potential realisations implies a highly computationally expensive and potentially infeasible process to find the optimal solution. Thus, a simulation-based technique is instead used to solve the problem. To keep the computational time within reasonable limits, we make two main simplifications. First, S^{CAP} is set to 1. This implies a maximum limit of one deployed batch in each period, and is a reasonable approximation to the general operational practice. Several, we let the harvesting variable h_t^L be decided by the criteria if either the local MAB limit or the company MAB limit will be exceeded in the following time period. If the latter MAB limit is exceeded, the harvesting will happen at the location containing the oldest batch.

In order to investigate both the production value and the operational risk related to the different productions, the production simulation is run in two steps. In the first step, the aim is to find the composition of the production plan providing the highest production value, disregarding the risk of sexual maturation. Simulation Step 1 gives insights into how the producer optimally can distribute all-male and all-female batches in a multiple location production to obtain the highest value of production. To model the choice of gender, we vary the probability of choosing all-female in each smolt deployment. When performing Step 1 of the simulation, the model first randomly determines in which of the available locations L to deploy smolt by setting the decision variable $s_t^{L,C}$ equal to 1. This implies that for each period valid for deploying, location L is drawn randomly from the set of all locations of with $\rho_t^L = 0$. Thereafter, the cohort C is decided given the probability of choosing all-female smolt. The other variables are as defined in Section 2.1, with the maturation rate z kept fixed at the median value of the given cohort. This implies that Step 1 contains no uncertainty, and hence involves deterministic simulating a large number of different production plans, to assess the properties of the optimal production. The optimal production plan then is found by running 1,000,000 simulations, which is considered sufficiently to achieve the predetermined accuracy.[3]

In Step 2, we stress test the optimal production plans found in simulation Step 1 by incorporating uncertainty in the sexual maturation rates. The solution space in simulation Step 2 is significantly decreased, as the production plans are kept fixed, and the simulations are thus only run 10,000 times for each given production plan. This is found to be sufficient to approximate the entire distribution of sexual maturation in the simulations.

3. Data

This section presents the input parameters used in our case study. The production data in our study is sourced from a research project led by AquaGen AS, selective breeding company which develops genetic material..[4] The purpose of this research project is to assess production optimization through modern breeding technology, and one of the focus areas is how mono-gender smolt, and specifically all-female smolt, can reduce operational risk and increase profits. Sea trials for mono-gendered cohorts were completed between May 2019 and August 2020. The trial consisted of three net pens, one with 115,852 female fish, one containing 115,384 male fish, and a mixed cohort of 115,346 fish. We calibrate growth and mortality rates based on 108, 112 and 120 samples from all-male, all-female and mixed cages, respectively. The sexual maturation rates are based on production data from eleven mixed-gender productions completed in the time period 2015–2020. In addition, quantity and weight of deployed smolt, seawater temperatures, MAB limit of the production sites and fallowing requirements are chosen to reflect production parameters of an actual salmon producer in Northern Norway with 17 production sites. The production cycle is set to last for five years, divided into time periods of one month. Salmon prices and the corresponding downgrade factor are based on data from the NASDAQ Salmon Index.

The growth rates are calculated based on temperature data for the different sites over the whole year from Aasen (2021) and TGC-values estimated from production data for up to 20 months obtained from spring-transferred smolt (S1). Fig. 1 illustrates the estimated TGC-values for the different cohorts, and shows that the average growth for both all-male and all-female in fact is higher than for mixed-gender.

Monthly mortality data for salmon of age up to 20 months in the sea is based on production data of both mixed and mono-gender batches. The mortality rates for the different cohorts over the complete production period are shown in Fig. 2. As can bee seen, both all-male and all-female do have lower mortality rates than mixed-gender.

The sexual maturation rates used in the simulation are based on the data from mixed-gender cohorts. Here, we assume that the maturation rates do not depend on whether the salmon is in a mixed gender or mono-gender cohort. The rates are assumed to follow a log-normal probability distribution. Fig. 3 illustrates the modelled probability distribution of the sexual maturation rates of male and female salmon. As is evident from the plots, male salmon have a significantly higher expected sexual maturation than female salmon. The sexual maturation rate for males is found to be 15.2% while it for females is found to be 0.14%. The standard deviations are 9.4% and 0.19%, respectively.

The prices used in the simulation are taken from the NASDAQ Salmon Index (FishPool, 2022). These are given as monthly prices and are further differentiated on the different weight classes. As a result of high demand and low supply of fish in the market, the prices in 2022 have seen historically high levels, and the price data used is characterised by high volatility (FishPool, 2022; Furuset, 2022). The prices are calculated as the three-year average[5] for the given month and given weight class, in order to limit the effect of price volatility in our simulation.

The downgrade factor is highly uncertain. The recent price increase has led to a large spread in premium and production quality fish prices, where the price difference has reached levels of roughly 35% (Furuset, 2022). In our simulation, the downgrade factor is set to be 30% for all months. The sensitivity related to changes in the downgrade factor is investigated in Section 5.

The parameters related to the specific production properties are based on the actual production data from the salmon farming company, Barentswatch (2022) and Fiskeridirektoratet (2021). The simulated production consists of ten different production sites, which are chosen randomly from the salmon farmer's 17 existing sites. This number is chosen as a trade-off between realistic simulation and computational complexity, where more sites require significantly more computational time. The MAB limits reflect the true limits of the production sites collected from Barentswatch (2022).

The initial weight and quantity of deployed salmon are set to be 100 g and 1,000,000 fish, respectively, in line with operational practice. For simplicity, both the initial weight and the quantity of fish in each deployment are set to be constant.

Production costs consist of smolt and harvesting costs. The cost of producing all-male smolt is 15.7 NOK/smolt, while that of all-female smolt is set at a lower rate of 13.0 NOK/smolt. The reason behind this difference is the employment of distinct technologies for the production of these smolts. All-male smolt is created using gender-sorting techniques such as ultrasound-sorting, as elaborated in Næve et al. (2019). This method also provides an equal number of all-female smolts that can be utilized in production. As a result, in our simulations, we only

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[3] The accuracy and required number of simulations are discussed in Appendix B.1.

[4] The project is connected to research licence from the Directorate of Fisheries "Produksjonsoptimalisering i verdikjede havbruk gjennom moderne avlsteknologi".

[5] Calculated as the average of the first week of all months in the period May 2019–May 2022.

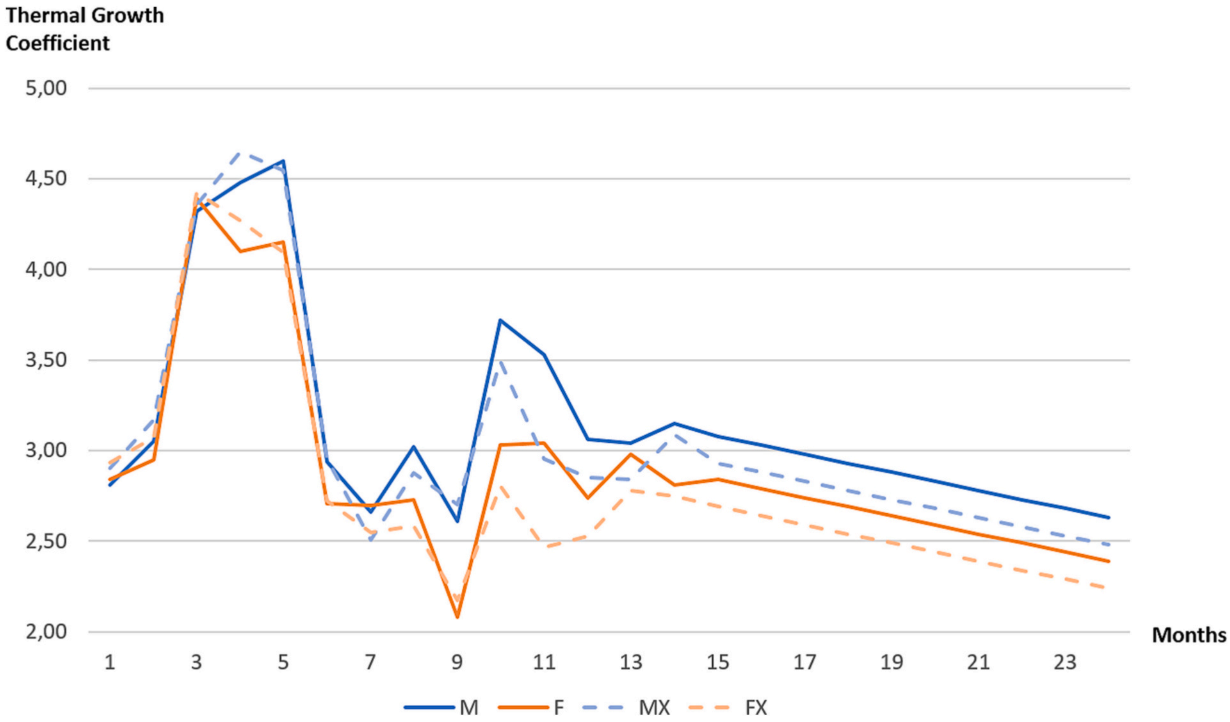


Fig. 1. TGC-values for the three different cohorts of spring transferred smolt.

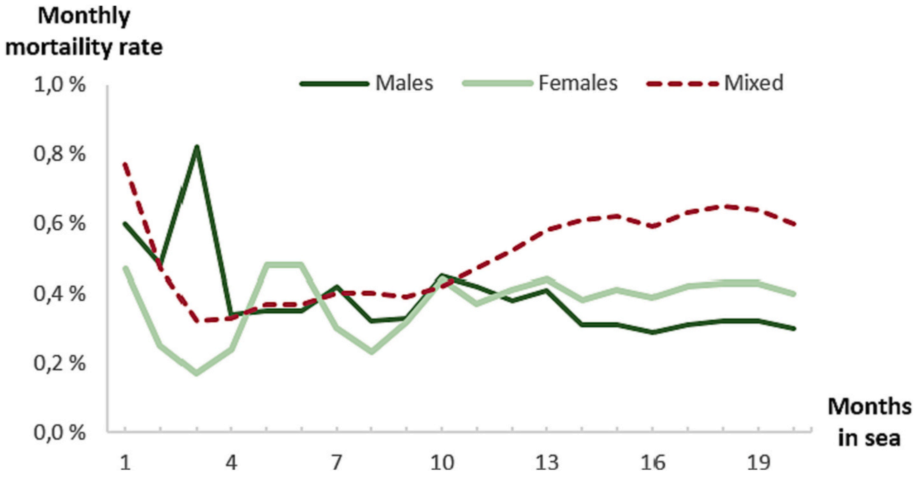


Fig. 2. Mortality rates for the three different cohorts.

consider production plans that contain more than 50% male smolts to ensure fair comparisons. The technology employed for all-female smolt production involves all-female roe production, which is more cost-effective. In Section 5.2, we investigate the sensitivity of our results with respect to the assumptions about smolt costs by setting the costs for all-male and all-female smolts to be equal. The cost of mixed-gender smolt is given to be 12.7 NOK/smolt.The harvesting costs are collected from Fiskeridirektoratet (2021), and are in our simulations set to be 4 NOK/kg.

4. Results

In this section, we present the main results from the simulation study. In particular, we test our hypothesis that mono-gender production offers more beneficial outcomes in terms of expected value and operational risk compared to mixed-gender smolt production practices. We start by presenting the results from Step 1 of the simulation, where we assess the properties and values of the optimal mono-gender and mixed-gender production plans. Next, we present the results from Step 2, where the optimal production plans are stress-tested by re-running the simulations with stochastic sexual maturation rates.

4.1. Step 1: simulation of different production plans

In this section, we simulate different production plans for different gender compositions with the sexual maturation degree z kept fixed at the median of the given cohort. The main results of the first simulation step are shown in Fig. 4, which illustrates the value of production as a function of the actual percentage of all-female deployments in the simulated productions, which we denote by γ. Recall that, in our simulations, we only consider production plans that contain more than 50% male smolts to ensure fair comparisons and optimal utilisation of

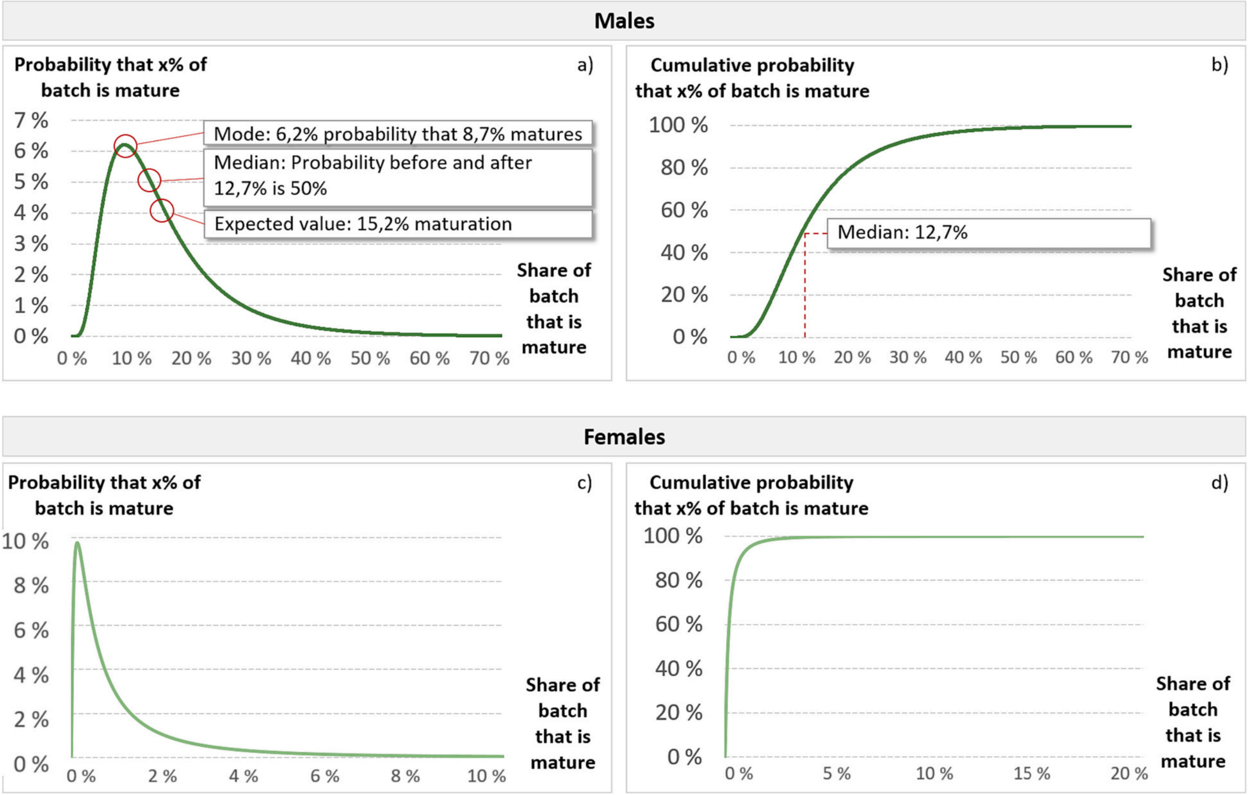


Fig. 3. Probability distribution of maturation for males: density function (a) and cumulative function (b), and for females: density function (c) and cumulative function (d).

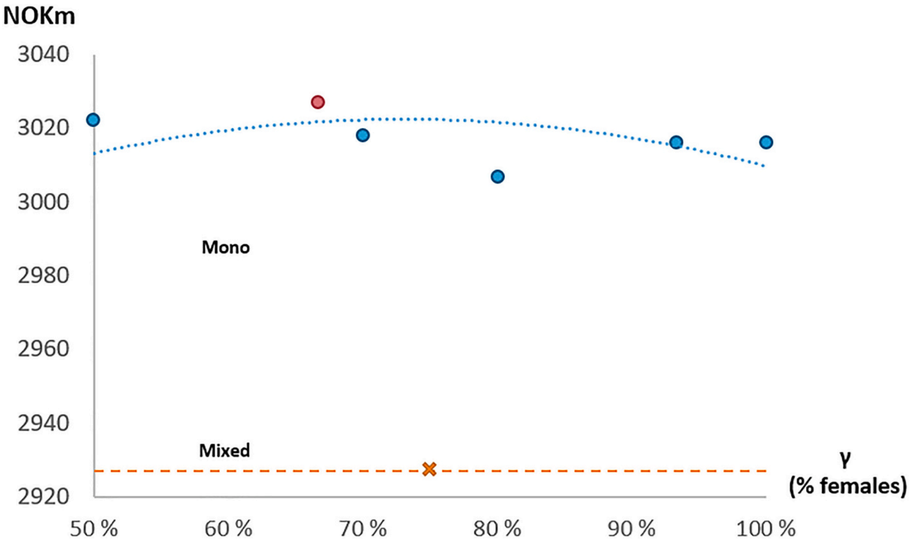


Fig. 4. Regression on best simulated productions as a function of γ.

resources, as female smolts are a byproduct of the gender sorting process used to produce all-male smolts. in Fig. 4, the dashed blue curve represents quadratic regression that best fits the eleven production values, while the orange line illustrates the value of the simulated mixed-gender production.

In Fig. 4, it is evident that the value of the simulated production is strongly dependent on the gender distribution, γ. Production values range from 3007 to 3027 NOKm. Although the value of mono-gender production is significantly affected by gender composition, Fig. 4 clearly shows that mono-gender outperforms mixed-gender in terms of production value, for all values of γ. Even the lowest mono-gender production value of 3007 NOKm, outperforms the one of mixed-gender production, equal to 2927 NOKm. Moreover, the highest mono-gender production value of 3027 NOKm is 3.4% higher than for the mixed-gender production. Fig. 4 also indicates that the production value is generally higher for increasing shares of female salmon in the production. Moreover, the production of only all-female salmon generates a value of 3016 NOKm. The highest production value is generated by the production with a γ of 67%, indicated as the red point in Fig. 4. This implies that the best production efficiency is achieved by including both genders in the production. As mono-gender production provides more possible combinations of production plans, it is expected that it is possible to find mono-gender productions that provide even higher production values, by simulating the production of even more γ-values. This is investigated in Appendix B.2.

Fig. 5 shows the distribution of different genders over the production cycle of the optimal production found at γ of 67%.

As can be seen, the value contribution from female deployments significantly outweighs the contribution from male salmon, with a roughly twice as large growth coefficient. This indicates that the optimal production value is achieved by having both all-male and all-female cohorts distributed relatively evenly over the whole production period. The production plan for the best found production with a γ of 67%, is illustrated in Appendix B.3.

In order to disentangle how the different properties of mono-gender production contribute to the increased value of production, we analyze the mono-gender production with equal share of females as in a mixed-gender batch (γ of 50%). In this case, the difference between mixed-gender and mono-gender productions is driven by three factors. First, mono-gender production provides higher flexibility in production planning. This relates to how the producer can utilise gender-specific properties of the cohorts by deploying them at different times and locations, hence achieving better exploitation of the production capacities. Second, mono-gender production achieves improved biologic properties of the salmon, with both higher growth rates and slightly lower mortality. This applies both to male and female salmon. Third, mono-gender smolt have higher costs than mixed-gender smolt, which favors mixed-gender production. To isolate the contribution of these three factors we run additional simulations with i) both the smolt costs and the biological properties of the gender set equal to as if the salmon was in a mixed-gender batch; ii) the mono-gender smolt costs set equal to the cost of mixed-gender smolt, but without adjusting the biological properties. The results are illustrated in Fig. 6.

As can be seen, the value related to the increased flexibility is 79 NOKm, representing an increase in total value of roughly 2.7%. Better genetic properties are found to increase the value of mono-gender production by 66 NOKm, or roughly 2.2%, compared to mixed. Conversely, the loss in value due to the higher cost of mono-gender smolt is found to be 50 NOKm, representing a decrease of roughly 2%. This finding indicates that the gain from better utilisation of the genetic properties outweighs the loss from the higher smolt cost of mono-gender production, which hence implies that the improved value of production is mainly released by the increased flexibility in production planning.

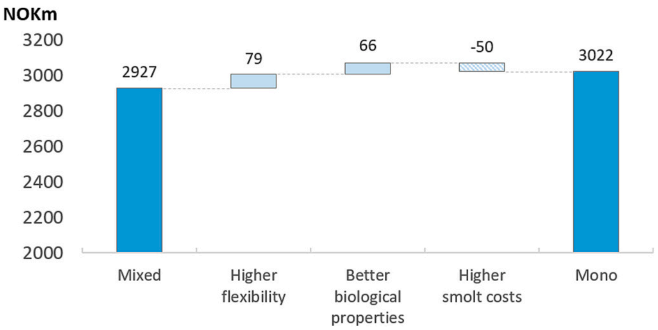


Fig. 6. Value contributions from different properties of the production.

4.2. Step 2: simulation with stochastic sexual maturation rates

In this section, we present the results of the second simulation step, which takes into account stochastic maturation rates. We compare these results with those from the first simulation step to assess the operational risk associated with the production plan under different risk preferences. Additionally, we investigate potential losses related to this risk using VaR and CVaR measures.

Fig. 7 shows the expected value of the production. The red lines indicate the 50% confidence interval for each production value, whereas the blue shaded area represents the 50% confidence interval of the regression based on the production values.

As can be seen, the confidence interval is wider for the productions with high shares of male salmon. This is because the risk of sexual maturation affects all-male batches more than all-female batches due to higher expected value and volatility in the sexual maturation rate. Thus, increasing the share of female salmon, i.e. higher values of γ, enable the producer to reduce the operational risk. Moreover, the possibility to choose deployments with different risk profiles enables producers to better fit the production to their risk preferences.

The expected value and standard deviation of all the simulated productions, along with the Value at Risk and Conditional Value at Risk related to each of the productions, are presented in Table 1.

As can be seen, the production with a γ of 67% still provides the highest expected production value, even when accounting for uncertainty in the sexual maturation rates. However, this plan's higher expected value comes with a higher associated risk. Specifically, its standard deviation of 2.5% indicates higher risk than the production plan with a γ of 100%, which has the second-highest expected value and a lower standard deviation of 1.4%. Therefore, the choice between the two production plans depends on the producers' risk preferences. The

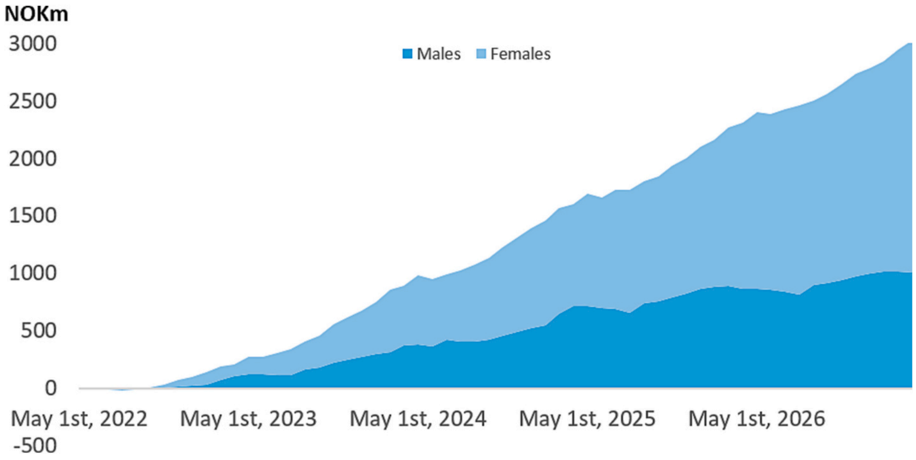


Fig. 5. Development in accumulated value split on gender for production with γ of 67%.

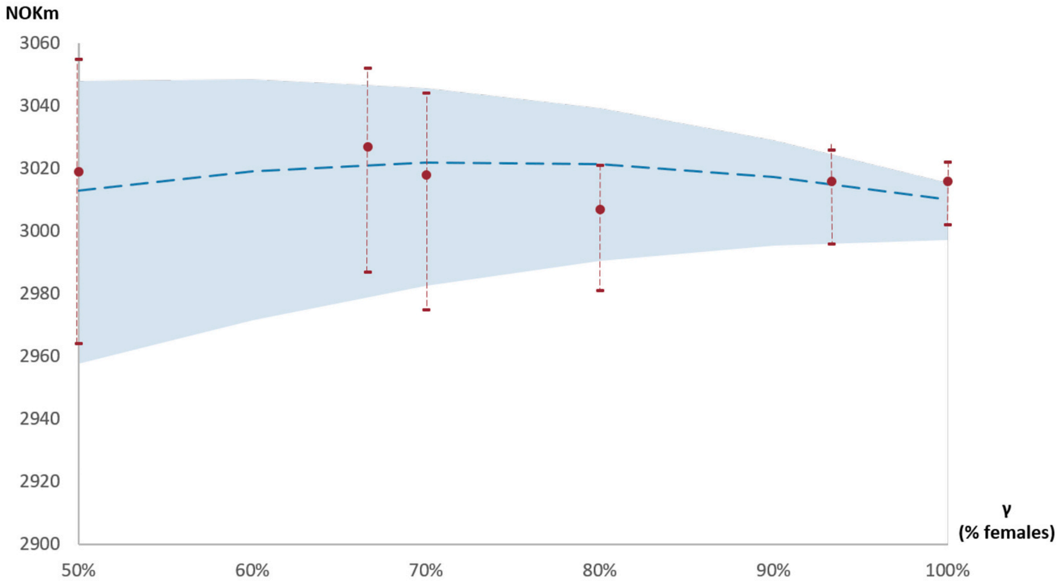


Fig. 7. Production values and 50% confidence interval with stochastic maturation rates.

Table 1
Expected value and related risk of the simulated productions.

Share of females (γ)	Statistical properties			Value-at-Risk						Conditional Value-at-Risk					
				90%		95%		99%		90%		95%		99%	
	Expected value	Median	Std. Dev.	NO Km	% of median	NOKm	% of median	NOKm	% of median	NOKm	% of median	NOKm	% of median	NOKm	% of median
100%	3004	3016	1.4%	42	1.4%	74	2.5%	190	6.3%	104	3.4%	152	5.0%	311	10.3%
93%	3002	3016	1.6%	55	1.8%	90	3.0%	214	7.1%	121	4.0%	172	5.7%	336	11.1%
80%	2990	3007	1.9%	69	2.3%	111	3.7%	252	8.4%	145	4.8%	203	6.8%.	384	12.8%
70%	2996	3018	2.7%	107	3.5%	164	5.4%	336	11.1%	203	6.7%	274	9.1%	480	15.9%
67%	3006	3027	2.5%	101	3.3%	156	5.2%	321	10.6%	193	6.4%	262	8.7%	461	15.2%
50%	2997	3022	3.2%	134	4.4%	200	6.6%	389	12.9%	241	8.0%	320	10.6%	535	17.7%
Mixed	2900	2927	3.4%	143	4.9%	213	7.3%	411	14.0%	256	8.8%	339	11.6%	565	19.3%

same conclusion applies to VaR and CVaR of simulated productions. The 90% VaR values show that the 90% worst-case scenario represents a loss of value of 101 NOKm for the production plan with a γ of 67%, whereas the corresponding loss for the plan with a γ of 100% is only 42 NOKm. Furthermore, if the 90% worst-case scenario is exceeded, the CVaR values indicate expected losses of 104 NOKm and 241 NOKm, respectively, for the two production plans. This implies that the production plan with the highest expected value is associated with a higher potential loss, which is more than twice as high as in the production plan with the lowest risk. This relationship also holds for the 95%- and 99%-VaR and the 95%- and 99%-CVaR. The difference in the expected value of the two production plans is, however, of only 2 NOKm, which emphasises the importance of accounting for risk when evaluating the different production options.

The trade-off between the production expected value and standard deviation is illustrated Fig. 8. The scatter plot includes the simulated productions and the regression curve.

Fig. 8 illustrates that mixed-gender production is sub-optimal when compared to mono-gender production, as it is associated with both a higher standard deviation and a lower production value. The figure also highlights the sub-optimality of a large share of mono-gender productions marked by grey crosses. The green rhombus indicates the simulated productions that are found to be efficient, which include the production plans with γ-values of 100% and 67%. These points illustrate the only γ-values where the producer cannot obtain a higher return at a lower risk, or vice versa. The production plan with a γ of 67% provides the highest production value, while the production plan with a γ of 100% is associated with a lower operational risk. Thus, both production plans are efficient, and the choice between them is dependent on the producers' risk preferences.

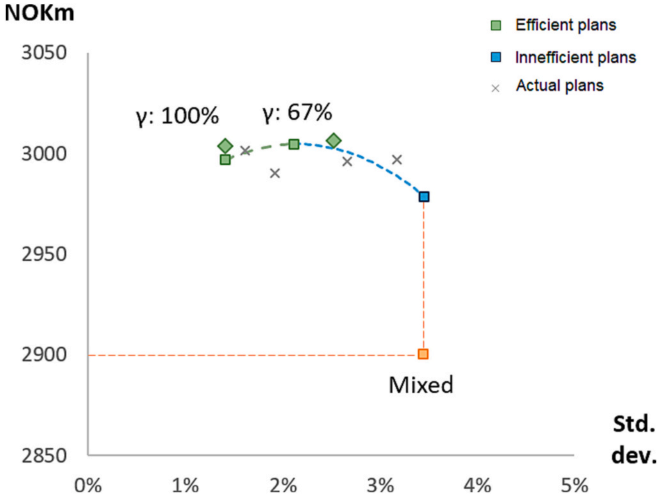


Fig. 8. Efficient frontier of γ-values in mono-gender production.

5. Sensitivity analysis

To investigate the robustness of our results with respect to changes in the decisive parameters, we perform a sensitivity analysis of the simulated productions. First, we run simulation Steps 1 and 2 for downgrade factors of 10% and 40%, which are generally subject to substantial variability. Secondly, we run the simulations for adjusted smolt costs. As smolt costs are associated with technological development, this allows us to assess how the optimal production solution potentially will be affected by new technology.

5.1. Varying the downgrade factor

Fig. 9 depicts the outcomes of the first simulation step for different downgrade factors. The green and red lines represent the production values for downgrade factors of 10% and 40%, whereas the blue line represents the value in our baseline case with a downgrade factor of 30%.

The figure clearly shows that the production value increases for lower downgrade factors. For lower downgrade factors, higher production values are achieved with a higher proportion of males. This is due to the fact that when downgrade factors are low, the consequences of sexual maturation are less severe, reducing the relative advantage of using female salmon. Nevertheless, the highest production values for all scenarios are achieved for higher shares of female salmon.

The effect of the downgrade factor on the value of the optimal production plan should, as in Section 4.1, also be evaluated in light of the operational risk related to the production. Fig. 10 illustrates the results from running simulation Step 2 on the production with downgrade factors of 10% and 40%.

The figure shows the expected value of the productions under each downgrade factor, together with the 50% confidence intervals. As is seen from the figure, the downgrade factor significantly affects the volatility of the production value, as the confidence interval is substantially tighter in the scenario with a downgrade factor of 10% than for a downgrade factor of 40% implying a significant change in potential losses for equal production plans under different scenarios.

By combining the expected value and operational risk properties of the productions, we are able to assess the efficient frontier of the production in each scenario. These are given in Fig. 11. As we see from the plots, changes in the downgrade factor affect which production compositions are found to be efficient. In the case with a downgrade factor of 10%, the productions with γ-values of 100%, 87%, 77% and 67% are all found to be efficient. The figure also shows that mixed-gender production is sub-optimal, as it cannot increase the risk/return profile in any of the scenarios.

The findings from the efficient frontiers illustrated in Fig. 11 summarise how changes in the downgrade factor affect both the expected value and operational risk of the productions. As seen from the figure, the only production that is efficient in all of the investigated scenarios is the production of only all-female salmon, with a γ of 100%. This is due to the lower maturation risk of female salmon implying the lowest risk in all scenarios. Furthermore, Fig. 11 shows that the γ-values of the efficient productions decrease with higher downgrade factors, indicating that risk-averse producers favour higher shares of all-female batches in production.

5.2. Similar smolt cost for all-male and all-female

Changes in smolt costs of the different gender cohorts are expected to affect both the value and the optimal γ of the production. Unlike the downgrade factor, the smolt costs are not characterised by high volatility. However, the prices can potentially change over time as a result of technological development. To analyze how this affects the production properties, simulation Step 1 is re-run with the cost of both all-male and all-female set equal to 13.0 NOK/smolt. This represents a scenario where technological development has led to lower costs of all-male smolt, such that they are equal to the cost of all-female smolt. The downgrade factor in the simulation is set to 30%, equal to the baseline case.

Fig. 12 indicates that the change in smolt cost significantly impacts the production value. When compared to Fig. 4, it is evident that the values of production overall have increased, due to the lower cost of all-male smolt. In addition, the value of production plans with high shares of male salmon slightly increases, as the cost advantage of all-female production is reduced. As can be seen, the best found production has a lower share of female fish, $\gamma = 53\%$, compared to our baseline case with $\gamma = 67\%$. The figure indicates, however, that a combination of both all-male and all-female batches still represents the most favourable option, and that the producer can obtain the best utilisation of the gender-specific properties by including both genders in the production.

5.3. Discussion

In the following we outline potential extensions of our analysis. Due to our focus on gender-specific properties of the production, uncertainty in the market prices is excluded from our modelling. This is done as price uncertainty affects both mono-gender and mixed-gender equally, and furthermore potentially entangles the effects from the gender-specific

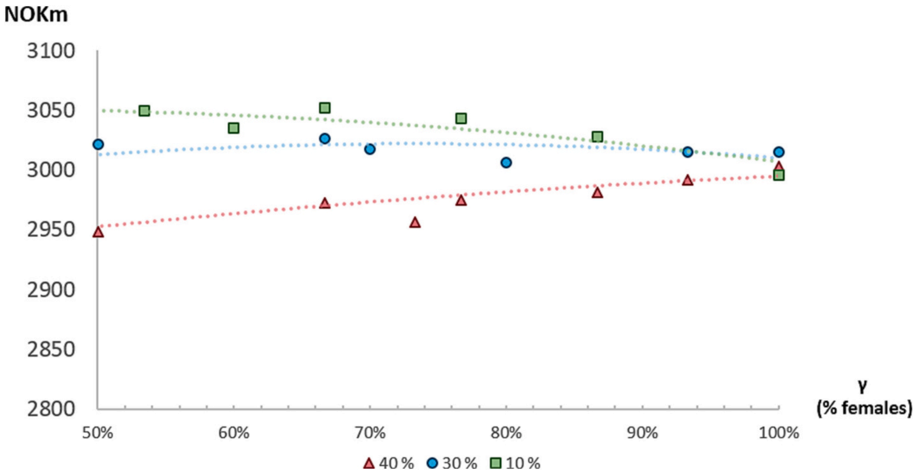


Fig. 9. Best simulated productions as functions of γ for different downgrade factors.

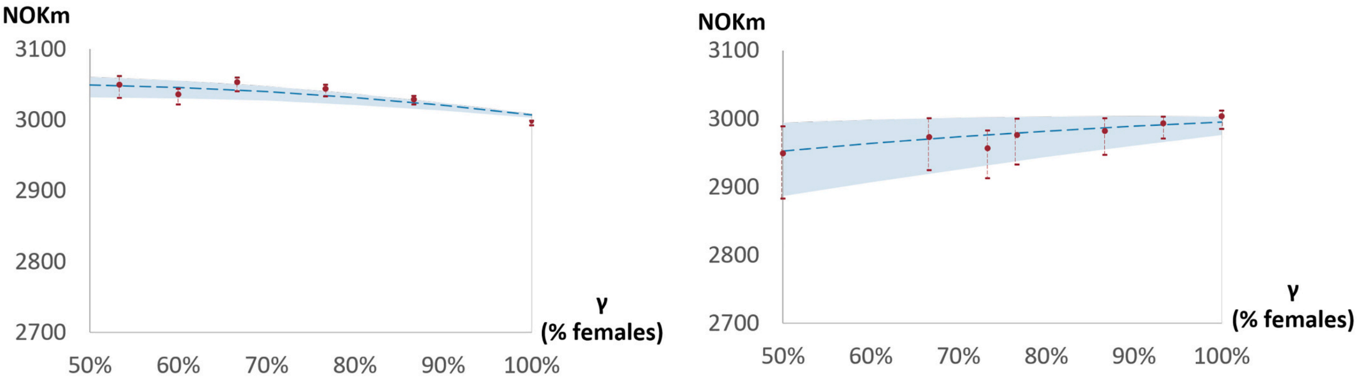


Fig. 10. Best productions and 50% confidence interval with stochastic maturation rates, for downgrade factors 0.1 (left) and 0.4 (right).

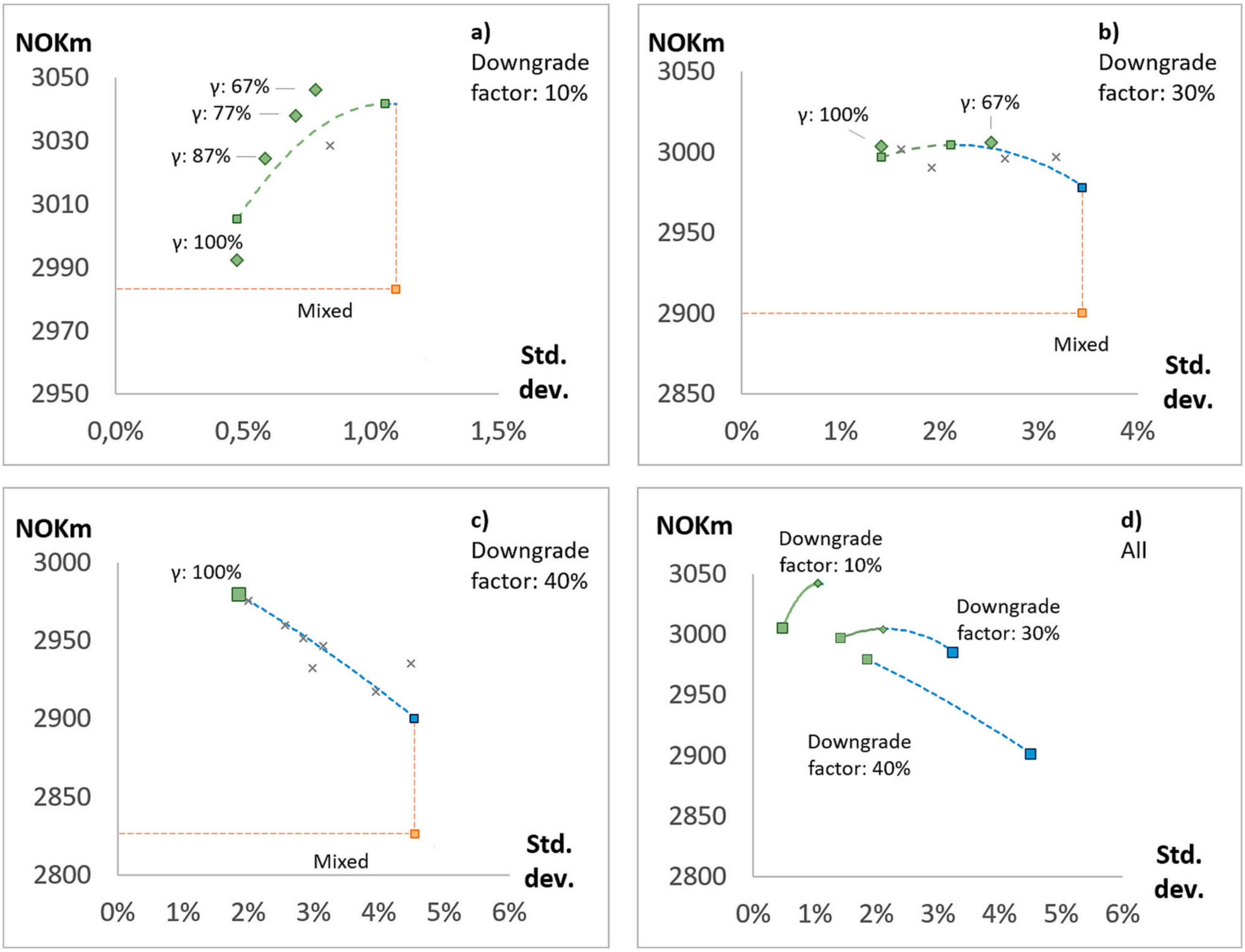


Fig. 11. Efficient frontier of γ values in mono-gender production for different downgrade factors.

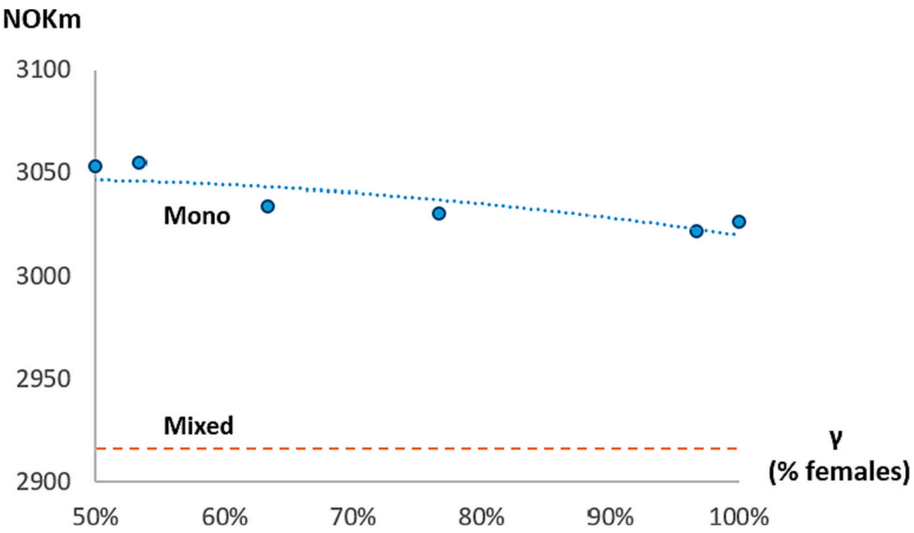


Fig. 12. Best simulated productions as functions of γ for similar cost of all-male and all-female smolt.

properties. Moreover, the cost of feeding and other variable costs of production are excluded due to the same arguments. However, including price uncertainty and additional measures of costs in the modelling could potentially provide new insights on how the production is affected by the inclusion of mono-gender smolt. The production in our simulation consists of ten locations, where each location consists of one net pen. A natural extension of this paper is to let each location consist of several net pens. Adding more net pens improves the possibility to utilise the gender-specific properties, and is further expected to increase the value of flexibility. Hence, by including this on our modelling, the favour of mono-gender production over mixed-gender production is expected to increase even more.

6. Conclusion

This paper investigates how the introduction of mono-gender smolt can increase production efficiency and reduce operational risk in Atlantic salmon farming. The analysis is based on simulations of multi-location productions of both mono-gender and mixed-gender salmon, where the value and associated risk of different production compositions under different scenarios are assessed. Our results show that, when accounting for gender-specific biological properties and smolt costs, mono-gender production outperforms mixed-gender production in terms of both operational risk and value of production. Thus, our findings imply a sub-optimality of mixed-gender production. The increased value of mono-gender production is found to be driven by better flexibility in the production planning and improved utilisation of the biological properties, and hence increased production efficiency. Moreover, our results show that the introduction of mono-gender smolt enables the producers to better adjust the production to reflect their risk preferences. This is shown to be of great importance to the production output under different scenarios, where operational risk factors are found to have a potentially significant impact on the production output.

CRediT authorship contribution statement

Maria Lavrutich: Conceptualization, Supervision, Methodology, Writing – review & editing. **Jonas Markussen:** Formal analysis, Conceptualization, Methodology, Writing – original draft. **Nore Rystad:** Formal analysis, Conceptualization, Methodology, Writing – original draft.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

This study was supported by the research licence from the Directorate of Fisheries connected to a project "Produksjonsoptimalisering i verdikjede havbruk gjennom moderne avlsteknologi" lead by AquaGen AS and NTNU with liscence number T-S-0022 and N-H-0046.

Data availability

Data will be made available on request.

Appendix A

Implementing the inverse cumulative distribution function in a programming model is not a straightforward approach, as the integral of the probability density function of a log-normal distribution does not have a closed-form solution. Nevertheless, we will explain one possible method, which is used in our modelling. Starting off with the basics, the variable X is log-normally distributed when $ln(X) \sim N(\mu, \sigma^2)$. Hence, the probability density function is given by

$$f_X(x) = \frac{1}{x\sigma\sqrt{2\pi}} \cdot exp\left(-\frac{(lnx-\mu)^2}{2\sigma^2}\right). \tag{A.1}$$

The corresponding cumulative distribution function is the integral of the probability density function, expressed as:

$$F_X(x) = \frac{1}{2}\cdot\left(1 - G\left(-\frac{lnx - \mu}{\sigma\sqrt{2}}\right)\right). \tag{A.2}$$

where the error function G(y) is given by:

$$G(y) = \frac{2}{\sqrt{\pi}}\int_0^y e^{-t^2}dy. \tag{A.3}$$

Introducing $G^{-}1(y)$ as the inverse function of G(y), we can restate Eq. (A.2) to the following expression:

$$x = exp\left(\mu + \sigma\sqrt{2}\cdot G^{-1}(2\cdot F_X(x) - 1\,).\right) \tag{A.4}$$

By substituting x with $p_t^C(z)$ and $F_X\left(p_t^C(z)\right)$ with z, we get the following expression:

$$p_t^C(z) = exp\left(\mu + \sigma\sqrt{2}\cdot G^{-1}(2\cdot z - 1)\right), \tag{A.5}$$

which mathematically expresses $p_t^C(z)$. However, we observe that $p_t^C(z))$ does not have a closed-form solution, due to the properties of G^{-1}. Thus, we apply an analytic technique in which we convert the probability density function into a Taylor series. After that, the expression is integrated term-by-term, where the sum of the terms is expressed as $\widetilde{p}$, which represents the approximated value of $p_t^C(z)$ for a given value of z.

Appendix B

Appendix B.1. Computational time

The required computational time of our model is relatively short, even for a large number of realisations. This implies that the required number of simulations can be found by simply running the simulations for an increased number of realisations until the change in the value of the best simulated result is less than the predetermined accuracy level. This represents a customary procedure, and works well for simulations with sufficiently low computational cost (Lerche and Mudford, 2005). This procedure is performed for both mono-gender and mixed-gender simulated production, where the number of simulations is multiplied by a factor of 10 until the desired accuracy level is reached. The simulation results are shown in Table B.2. As is clear from the table, the increase in best solution from 100,000 to 1,000,000 simulations is of 0.3% and 0.48% for mono-gender and mixed-gender production respectively, and 1,000,000 is hence chosen as the required number of simulations. The choice of 0.5% was a trade-off between required computational time and requirement of preciseness.

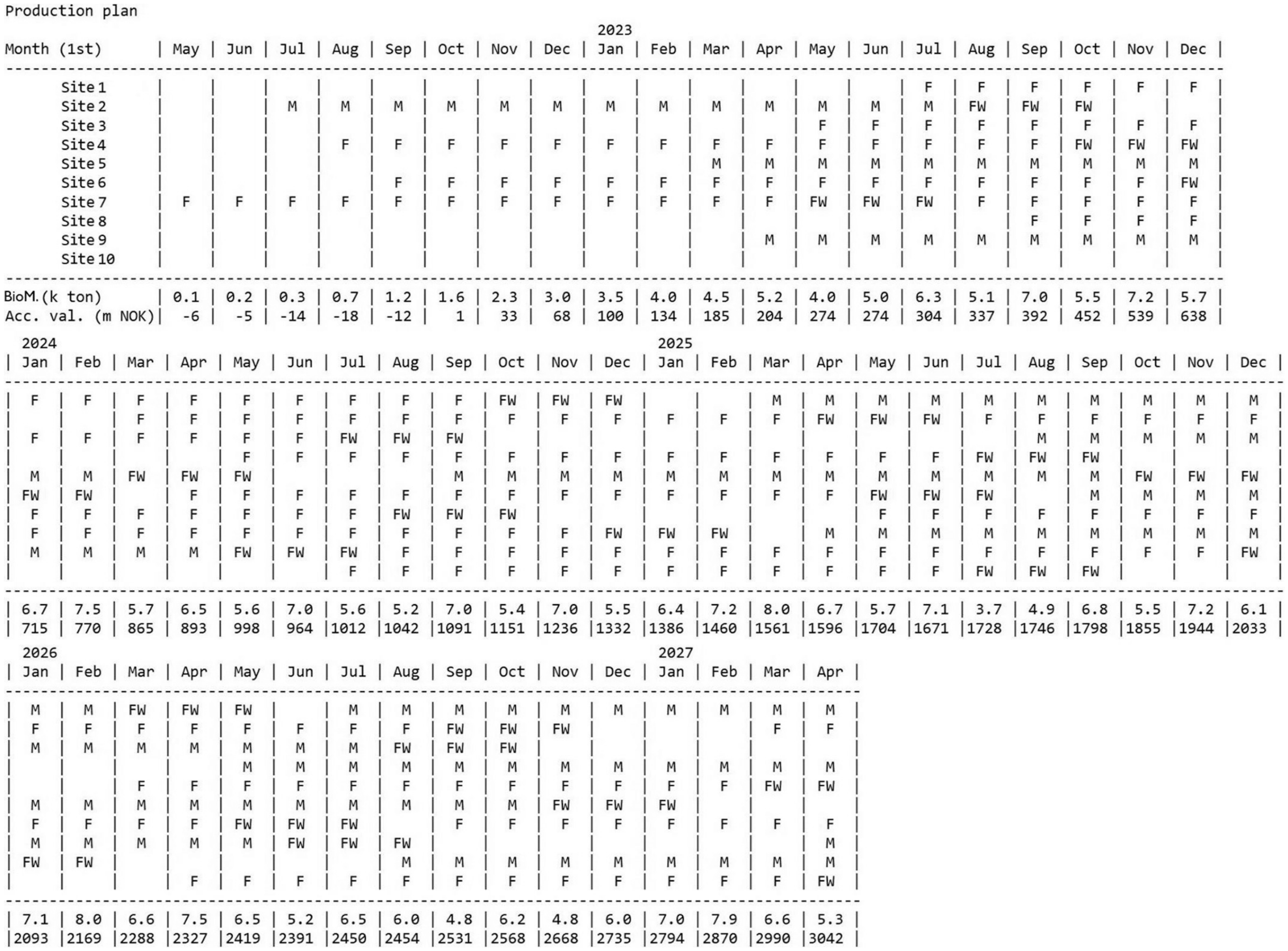
Table B.2
Best values of mixed and mono-gender ($\alpha = 50\%$) production for different number of simulations.

Summary of result with different number of simulations				
# Simulations	Mono ($\boldsymbol{\alpha} = \mathbf{50}\%$)		Mixed	
	Best achieved result (NOKm)	% increase	Best achieved result (NOKm)	% increase
1000	2945		2866	
10,000	3003	1.97%	2897	1.08%
100,000	3013	0.33%	2913	0.55%
1,000,000	3022	0.30%	2927	0.48%

Appendix B.2. Simulation accuracy

In Step 1 of the simulation we cover a large span of gender compositions by varying the probability of choosing all-female in each smolt deployment, which is denoted by α. Specifically, we consider the values of α between 0% to 100% with a step of 10% in the simulated productions. In order to investigate the potential for providing even higher value from the mono-gender production, the simulation is run multiple more times for α between 61% and 73%. More specifically, the simulations are run 1,000,000 times for α of 61%, 63%, 65%, 67%, 69%, 71% and 73%. The α values are chosen to span the area where we expect the best production plan to exist, as the highest production plan found so far has a γ of 67%. By running these simulations, we obtain a higher value of the simulated production, found at a γ of 60%. This production is found to have a value of 3043 NOKm, which outperforms the production value of the best production found at γ 67% with roughly 0.8%. This finding indicates the potential for mono-gender production to provide even better results, if more production compositions are investigated.

Appendix B.3. Best production plan



```
Production plan
                                                                  2023
Month (1st)      | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
------------------------------------------------------------------------------------------------------------------------------------------
      Site 1     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |  F  |  F  |  F  |  F  |  F  |  F  |
      Site 2     |     |     |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  | FW  | FW  | FW  |     |     |
      Site 3     |     |     |     |     |     |     |     |     |     |     |     |     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |
      Site 4     |     |     |     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  | FW  |
      Site 5     |     |     |     |     |     |     |     |     |     |     |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |
      Site 6     |     |     |     |     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  |
      Site 7     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  | FW  |  F  |  F  |  F  |  F  |  F  |
      Site 8     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |  F  |  F  |  F  |  F  |
      Site 9     |     |     |     |     |     |     |     |     |     |     |     |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |
      Site 10    |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
------------------------------------------------------------------------------------------------------------------------------------------
BioM.(k ton)     | 0.1 | 0.2 | 0.3 | 0.7 | 1.2 | 1.6 | 2.3 | 3.0 | 3.5 | 4.0 | 4.5 | 5.2 | 4.0 | 5.0 | 6.3 | 5.1 | 7.0 | 5.5 | 7.2 | 5.7 |
Acc. val. (m NOK)|  -6 |  -5 | -14 | -18 | -12 |   1 |  33 |  68 | 100 | 134 | 185 | 204 | 274 | 274 | 304 | 337 | 392 | 452 | 539 | 638 |
  2024                                                                    2025
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
-------------------------------------------------------------------------------------------------------------------------------------------------
|  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  | FW  |     |     |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |
|     |     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  | FW  |  F  |  F  |  F  |  F  |  F  |  F  |
|  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  | FW  |     |     |     |     |     |     |     |     |     |     |  M  |  M  |  M  |  M  |  M  |
|     |     |     |     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  | FW  |     |     |     |
|  M  |  M  | FW  | FW  | FW  |     |     |     |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  | FW  | FW  | FW  |
| FW  | FW  |     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  | FW  |     |  M  |  M  |  M  |  M  |
|  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  | FW  |     |     |     |     |     |     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |
|  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  | FW  |     |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |
|  M  |  M  |  M  |  M  | FW  | FW  | FW  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  |
|     |     |     |     |     |     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  | FW  |     |     |     |
-------------------------------------------------------------------------------------------------------------------------------------------------
| 6.7 | 7.5 | 5.7 | 6.5 | 5.6 | 7.0 | 5.6 | 5.2 | 7.0 | 5.4 | 7.0 | 5.5 | 6.4 | 7.2 | 8.0 | 6.7 | 5.7 | 7.1 | 3.7 | 4.9 | 6.8 | 5.5 | 7.2 | 6.1 |
| 715 | 770 | 865 | 893 | 998 | 964 |1012 |1042 |1091 |1151 |1236 |1332 |1386 |1460 |1561 |1596 |1704 |1671 |1728 |1746 |1798 |1855 |1944 |2033 |
  2026                                                                    2027
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr |
-------------------------------------------------------------------------------------------------
|  M  |  M  | FW  | FW  | FW  |     |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |
|  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  | FW  |     |     |     |  F  |  F  |
|  M  |  M  |  M  |  M  |  M  |  M  |  M  | FW  | FW  | FW  |     |     |     |     |     |     |
|     |     |     |     |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |
|     |     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  | FW  |
|  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  | FW  | FW  | FW  |     |     |     |
|  F  |  F  |  F  |  F  | FW  | FW  | FW  |     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |
|  M  |  M  |  M  |  M  |  M  | FW  | FW  | FW  |     |     |     |     |     |     |     |  M  |
| FW  | FW  |     |     |     |     |     |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |  M  |
|     |     |     |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  |  F  | FW  |
-------------------------------------------------------------------------------------------------
| 7.1 | 8.0 | 6.6 | 7.5 | 6.5 | 5.2 | 6.5 | 6.0 | 4.8 | 6.2 | 4.8 | 6.0 | 7.0 | 7.9 | 6.6 | 5.3 |
|2093 |2169 |2288 |2327 |2419 |2391 |2450 |2454 |2531 |2568 |2668 |2735 |2794 |2870 |2990 |3042 |
```

Fig. B.13. Production plan for production with γ 67%.

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