The economic benefit of herd genotyping and using sexed semen for pure and beef-on-dairy breeding in dairy herds

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ABSTRACT

The cost benefits of herd genotyping and the benefits of using sexed semen have been affected by recent improvements in sexing technologies, the incorporation of direct health traits in the German total merit index for Holstein cattle, the deteriorating prices for purebred heifer calves and bull calves, and the introduction of herd genotyping programs. Inseminating the genetically superior dams with female-sexed Holstein semen increases the mean breeding value of the heifer calves and can produce more Holstein heifer calves than are needed for replacement. This provides an opportunity to increase the selection response in health and production traits at the farm level.

A deterministic model is introduced that predicts the increase or decrease in net profit when a farmer takes part in a herd genotyping program and follows a certain insemination strategy. The types of semen that are allocated to cows and heifers are sexed semen or unsexed semen and Holstein semen or beef breed semen. The genetically superior heifers and cows are inseminated with female-sexed Holstein semen, intermediate dams with unsexed Holstein semen, and genetically inferior dams with unsexed or male-sexed beef breed semen.

In general, participating in a herd genotyping program is beneficial for German Holstein breeders. The optimum proportion of cows that should be inseminated with unsexed beef breed semen was found to be approximately 40%. In a herd with a low replacement rate, the selected heifers can exhibit their genetic superiority over a longer period of time, and a larger proportion of cows can be inseminated with beef breed semen. Participation in a herd genotyping program is, therefore, particularly beneficial for herds with low replacement rates.

Keywords: dairy cattle, genetic gain, herd genotyping, beef on dairy, sexed semen

INTRODUCTION

The dairy industry has changed dramatically in recent decades. In the 1990s, many farms struggled to raise a sufficient number of heifers to replace all of the culled cows. Breeding cows for improved health and fertility decreased the replacement rate in the northern part of Germany from 41% in 2004 to 31% in 2019 (Junge, 2020). This corresponds to an increase in the length of productive life from 2.44 years to 3.23 years. This trend reversal was initiated by the introduction of the total merit index (Relativ Zuchtwert Gesamt, RZG) in Germany in 1996. A further increase in the length of productive life is currently hindered by the fact that aging cows have to compete with heifers. The increase in the length of productive life led temporarily to an erosion of the prices for Holstein heifer calves. The introduction of genomic estimated breeding values (GEBVs) in 2010, the introduction of breeding value estimation for direct health traits in 2019, and the incorporation of these values into the newly introduced total merit index (Relativ Zuchtwert Euro, RZE) in 2020 in Germany accelerated the trend toward increasing health and length of productive life.

The established structures in cattle breeding enable a significantly higher selection intensity for sires than for dams. This results in production herds lagging significantly behind the breeding population in terms of performance traits as well as health traits. The genetic deficit of the production herds could be reduced by
increasing the selection intensity on the female side. For example, farmers may use female-sexed semen to increase the pool from which to select female offspring. Reducing the genetic lag of production herds could lead to more cows from production herds being suitable dams of sires, which could help preserve genetic diversity. Moreover, since the genetically superior offspring often come from cows with the highest estimated breeding values (EBVs), cows with low EBVs could be mated with male-sexed semen or unsexed semen of a beef breed, which is indeed being practiced to an increasing extent.

The trend toward improved health and longevity has been strengthened in recent years by the introduction of herd genotyping programs that allow informed selection decisions concerning calves to be made at an early age. German herd genotyping programs allow farmers to obtain GEBVs for their heifer calves at 14 d of age.

In general, the identification of the genetically superior animals can either be based on pedigree-based best linear unbiased prediction (BLUP) of the breeding values, which provides pedigree-based EBVs. Another method that includes genomic information is genomic BLUP which produces GEBVs and requires the animals to be genotyped. On the one hand, EBVs can be used to decide after the birth of a heifer calf whether it should be raised for replacement or sold for fattening. On the other hand, the EBVs can be used to decide which cows should be inseminated with dairy breed semen to serve as potential dams of cows and which cows should be used for crossbreeding to produce calves for fattening. Selection among the calves is only possible if more dairy breed heifer calves are born than are required for replacement. The Mendelian sampling effects, which are passed on from the parents to the calves, can, therefore, only be utilized for increasing selection response if more dairy breed heifer calves are born than are needed.

The dairy industry has profited not only from improved breeding methods but also from other technological improvements. In particular, improved methods for semen sexing have increased conception rates. Before 2014, it was generally agreed that sexed semen reduces the conception rate by 20% to 30%. However, several recent studies have reported reduced reductions in conception rates with sexed semen, which have been attributed to technological advances. A reduction in the conception rate of approximately just 15% was reported (Holden and Butler, 2018; Oikawa et al., 2019). While the formerly low conception rate for sexed semen allowed its use only with heifers, the improved conception rate makes sexed semen also of interest for use with cows. Male-sexed semen from beef breeds may be used with genetically inferior cows to produce crossbred offspring for fattening, while female-sexed semen from dairy breeds may be used on genetically superior heifers and cows to produce purebred heifer calves for replacement. The use of sexed semen in Germany has indeed increased in recent years not only for heifers but also for cows. However, sexed semen is currently approximately 20 € more expensive than conventional semen, and approximately 10% of resulting calves are of the undesired sex (DeJarnette and Seidel, 2021).

An economic evaluation of different strategies for using sexed semen and for implementing herd genotyping requires the breeding values to be expressed in monetary terms. The recently introduced economic total merit index RZ€ in German Holsteins meets this requirement. The RZ€ predicts the expected difference in profit or loss that a cow achieves in its lifetime compared with the population mean. This is done on the basis of an economic evaluation of all breeding value traits. The economic consequences of improving each trait were calculated by assuming that all other traits remained constant. Therefore, it is not taken into account, for example, that an increase in longevity also leads to a cow giving more milk in its lifetime. It is, however, incorporated into the calculation that the increase in longevity results in lower replacement costs. The RZ€ of a cow can, therefore, be interpreted as the profit difference of a cow per year, multiplied by the mean length of productive life. This is indeed what is needed for economic evaluations.

Approaches for the economic evaluation of selection and insemination strategies at the farm level include bioeconomic stochastic simulations (McCulloch et al., 2013; Cottle et al., 2018; Ettema et al., 2017) and a deterministic approach that involves the direct computation of the farmer's expected net benefit (Newton et al., 2018). Although Newton et al. (2018) did not consider beef breed semen and assumed that sexed semen is used on unselected cows and heifers, the deterministic approach has the strong advantage of being easy to implement in an Excel spreadsheet that can be filled in by farmers. The sensitivity of the optimum strategy to economic parameters and farm-specific peculiarities that was revealed by previous studies emphasizes the need for such a tool.

The aim of this study was to derive formulas for predicting the net benefit per cow that arises from taking part in a herd genotyping program and from strategically using sexed semen technologies and beef breed semen. The model accounts for the possibility of using female-sexed semen on genetically superior cows and for the possibility of using male-sexed or unsexed beef-breeding semen on genetically inferior cows. The model is evaluated with the example of a typical German Holstein farm and is implemented in an Excel spreadsheet that can be filled in by farmers.
MATERIALS AND METHODS

Materials

The model parameters were obtained from agricultural magazines for livestock production, scientific publications, price lists for semen and artificial insemination services of various breeding organisations, the yearbook of the Bundesverband Rind und Schwein e.V., the ‘Markt Bilanz Vieh und Fleisch 2021’ of the ‘Agrarmarkt Informations-Gesellschaft mbH’, publications of the ‘Vereinigte Informationssysteme Tierhaltung w.V.’, and from surveys of the ‘Arbeitsgemeinschaft Süddeutscher Rinderzucht- und Besamungsstationen e.V.’.

Scenarios and assumptions

Different scenarios are compared using the example of a typical German Holstein farm with 100 cows. It is assumed that the farm only rears the calves needed for replacement and sells the remainder at 14 d of age. The farmer decides which calves to raise based on their EBVs. For farmers who carry out herd genotyping, the selection criterion is the GEBV of the calf; for the others, it is the pedigree-based EBV.

It is assumed that farmers are not restricted to a fixed calving interval of one year. We assume that the intended calving interval of the farm is sufficiently long such that the farmer is able to set the start of insemination earlier when semen with low fertilization capacity is used. This allows the farmer to maintain the intended calving interval on average. Hence, the calving interval does not depend on the semen type. The maximum number of inseminations is chosen such that fertile cows have a 90% chance of becoming pregnant. The semen type that is used for a cow does not change between inseminations.

It is assumed that the farmer inseminates the genetically superior cows with female-sexed semen and the cows with average EBVs with unsexed semen, and that beef breed sires are used for genetically inferior cows. For insemination with a beef breed bull, the farmer can use either unsexed semen or male-sexed semen. The proportion of cows that are inseminated with a certain type of semen are parameters that the farmer could choose optimally. The optimization is carried out with the Excel add-in ‘Solver’, which uses a generalized reduced gradient method for solving nonlinear problems. Different values are obtained for heifers and cows. The proportions for cows and heifers were restricted to be nonnegative numbers that add up to one for both age classes. The parameters that are optimized are thus

- \( p_c \): The proportion of cows (heifers) inseminated with female-sexed semen from a dairy breed bull,
- \( p_u \): The proportion of cows (heifers) inseminated with unsexed semen from a dairy breed bull,
- \( p_{Bu} \): The proportion of cows (heifers) inseminated with male-sexed semen from a beef breed bull,
- \( p_{Bu} \): The proportion of cows (heifers) inseminated with unsexed semen from a beef breed bull.

The strategy followed by a farmer is determined by the choices for these parameters and by whether the farmer is taking part in a herd genotyping program.

The strategies under consideration are shown in Table 1. Scenarios A1 and A2 determine the economic benefit of herd genotyping. Scenario A1 assumes herd genotyping, while scenario A2 assumes no herd genotyping. Both scenarios pose no restrictions on the proportions of cows and heifers that are inseminated in a certain way, and determine the optimum proportions.

Scenarios A3 and A4 both ban the insemination of heifers with beef breed semen, while Scenario A4 bans additionally the insemination of cows with sexed semen. For the scenarios A3 - A4 it was determined whether herd genotyping was beneficial or not, and only the results from the optimum strategy are reported. Scenario A3* differs from scenario A3 in that surplus heifer calves are sold for replacement, while all other scenarios assume that they are sold for fattening. Scenario A5 assumes the exclusive use of Holstein semen and no herd genotyping.

Scenarios B1 and B2 were set up for determining how much the genetic standard deviation in the selection index could decline until herd genotyping would be no longer beneficial over selection based on pedigree-based EBV. Both scenarios banned the insemination of heifers with beef breed semen. Scenario B1 assumes herd genotyping, while scenario B2 assumes no herd genotyping.

Each scenario is compared with a reference scenario, which assumes that the herd is not genotyped, and that all cows are inseminated with unsexed dairy-breed semen. All other parameter values were chosen as in the scenario under consideration. When compared with the reference scenario, the strategy followed by a farmer can lead to an additional revenue, \( \Delta \text{rev}_{\text{gain}} \), from accelerated genetic gain and an additional revenue, \( \Delta \text{rev}_{\text{calf}} \), from the sale of calves. However, there can also be additional insemination costs, \( \Delta \text{cost}_{\text{semen}} \), and additional...
genotyping costs, $\Delta \text{cost}_{\text{geno}}$. For a farm with $N$ cows, the additional income of the farm per cow is computed as

$$\Delta \text{Inc} = \frac{1}{N} (\Delta \text{rev}_{\text{gain}} + \Delta \text{rev}_{\text{calf}} - \Delta \text{cost}_{\text{semen}} - \Delta \text{cost}_{\text{geno}}).$$

All scenarios without herd genotyping assumed that selection is based on the traditional total merit index RZG. The RZG has a correlation larger than 0.95 with the RZ€. The reason for using the RZG in the reference scenario is that the RZ€ is currently not computed for ungenotyped calves. To make fair comparisons, the RZG level of the herd was adjusted such that $\Delta \text{rev}_{\text{gain}} = 0$ was achieved when only unsexed dairy-breed semen was used and as many heifer calves were born as needed for replacement. Note that the German selection indices are used for illustration. The model equations can easily be adapted to other selection indices.

The additional revenues and costs $\Delta \text{rev}_{\text{gain}}$, $\Delta \text{rev}_{\text{calf}}$, $\Delta \text{cost}_{\text{semen}}$, and $\Delta \text{cost}_{\text{geno}}$ are obtained by subtracting the revenues and costs in the reference scenario from the revenues and costs $\text{rev}_{\text{gain}}$, $\text{rev}_{\text{calf}}$, $\text{cost}_{\text{semen}}$, and $\text{cost}_{\text{geno}}$ in the scenario under consideration. Formulas for computing the revenues and costs are derived below. Whenever possible, formulas are derived with the example of the cows. The equations for heifers are analogous. The parameters, their default values and their meanings are summarized in Tables 2–5. The farmers who use the Excel sheet are free to choose their own parameter values.

### Farm Characteristics

A German Holstein farm with $N = 100$ cows, a calving interval, $c_I$, of 411 days, and a replacement rate, $p_{\text{rep}}$, of 30% is considered. Fertile cows are inseminated until they are pregnant with a probability, $p_{\text{preg}}$, of 90% (97% for heifers) and are culled if they do not become pregnant. The proportion of culled cows that leave the farm because they do not become pregnant, $p_{\text{not\_preg}}$, equals 25%. These parameters are summarized in Table 2.

The cows can be assigned to the groups shown in Table 3. One group contains the $N_c$ cows that are successfully inseminated and are not culled, and one group contains the $N_c \text{ culleq}$ cows that are culled for diverse reasons. Cows from different groups differ in the average number of inseminations they receive. The other symbols shown in Table 3 are explained in detail below.

In total, $N_h = p_{\text{rep}} N = 30$ heifers and $N_c = N(365/c_I) - N_h = 58.8$ cows need to be successfully inseminated per year. Cows do not give birth to a calf after their last
The number of cows that are inseminated each year can be broken down as

\[ N_{\text{called}} = N_{c}^{\text{not preg}} + N_{c}^{\text{not preg}} + N_{c}^{\text{diverse}} \]

where \( N_{c}^{\text{not preg}} \) is the number of fertile cows that did not become pregnant by chance, \( N_{c}^{\text{not preg}} \) is the number of cows that became infertile during their last lactation, and \( N_{c}^{\text{diverse}} \) is the number of cows that are culled for reasons other than infertility. The numbers are calculated as follows. The number of cows that are called because they did not become pregnant equals \( N_{c}^{\text{not preg}} = p_{\text{not preg}} N_{c}^{\text{called}} = 7.5 \), while the number of cows that are called for reasons other than infertility equals \( N_{c}^{\text{diverse}} = N_{c}^{\text{called}} - N_{c}^{\text{not preg}} = 22.5 \). As the number of fertile cows that are to be inseminated each year equals \( N_{c}^{\text{inssem}} = N_{c} = 65.3 \), we have

\[ N_{c}^{\text{not preg}} = N_{c}^{\text{inssem}} (1 - p_{\text{preg}}) = 6.5 \]

and

\[ N_{c}^{\text{not preg}} = N_{c}^{\text{not preg}} - N_{c}^{\text{not preg}} = 1.0 \]

The presence of infertile cows implies that the observable pregnancy rate decreases from one insemination to the next.

Proceeds from the Sale of Calves

By using female-sexed semen on the genetically superior cows, the farmer can inseminate a larger proportion of genetically inferior cows with beef breed bulls to achieve higher calf prices. It is assumed that the proportion of calves with the desired sex, \( p_{u} \), is 50% for unsexed semen, while the proportion, \( p_{s} \), is 90% for sexed semen. On average, among the \( N_{c} \) successfully inseminated cows,

\[ N_{\theta}^{c} = N_{c} \left[ p_{u} p_{s} + p_{s} p_{s} \right] \text{ are pregnant with dairy heifer calves,} \]

\[ N_{c}^{\text{not preg}} = N_{c} \left[ 1 - p_{u} \right] p_{s} + \left[ 1 - p_{s} \right] p_{s} \text{ are pregnant with dairy bull calves,} \]

\[ N_{c}^{\text{not preg}} = N_{c} \left[ 1 - p_{u} \right] p_{Bu} + \left[ 1 - p_{s} \right] p_{Bu} \text{ are pregnant with crossbred heifer calves, and} \]

\[ N_{c}^{\text{not preg}} = N_{c} \left[ 1 - p_{u} \right] p_{Bu} + \left[ 1 - p_{s} \right] p_{Bu} \text{ are pregnant with crossbred heifer calves, and} \]

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\[ N_{c}^{\text{not preg}} = N_{c} \left[ 1 - p_{u} \right] p_{Bu} + \left[ 1 - p_{s} \right] p_{Bu} \text{ are pregnant with crossbred heifer calves, and} \]
Table 3: Symbols used to denote numbers of cows and heifers that fulfill specific requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default value</th>
<th>Parameter Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_c^prog</td>
<td>6.5</td>
<td>Fertile cows that are culled per year because they did not get pregnant by chance</td>
</tr>
<tr>
<td>N_c^infertile</td>
<td>1.0</td>
<td>Infertile cows that are culled per year because they did not get pregnant</td>
</tr>
<tr>
<td>N_c^diverse</td>
<td>22.5</td>
<td>Cows that are culled per year for reasons other than infertility</td>
</tr>
<tr>
<td>N_c</td>
<td>58.8</td>
<td>Cows that become pregnant per year and are not culled</td>
</tr>
<tr>
<td>N_c^prog</td>
<td>7.5</td>
<td>Cows that are culled because they did not get pregnant (N_c^prog + N_c^infertile)</td>
</tr>
<tr>
<td>N_c_culled</td>
<td>30.0</td>
<td>Cows that are culled per year (N_c + N_c_culled)</td>
</tr>
<tr>
<td>N_insem</td>
<td>88.8</td>
<td>Cows that are inseminated per year (N_c + N_c_culled)</td>
</tr>
<tr>
<td>N</td>
<td>100.0</td>
<td>Total number of cows</td>
</tr>
<tr>
<td>N_h</td>
<td>30.0</td>
<td>Replacement heifers that become pregnant per year</td>
</tr>
<tr>
<td>N_preg</td>
<td>88.8</td>
<td>Number of pregnancies per year from animals that are not culled (N_c + N_h)</td>
</tr>
</tbody>
</table>

\[ N_{XB} = N_c \left( p_u \, p_{Bu} + p_p \, p_{Bs} \right) \] are pregnant with crossbred bull calves.

By assuming a rearing loss, \( r_{14} \), of 2% from Day 3 to Day 14 and the stillbirth rates \( s_{c} \), given in Table 4, the farmer obtains on average

\[ \tilde{N}_c = N_c \left(1 - s_{c}\right) \] dairy breed heifer calves,

\[ \tilde{N}_b = N_b \left(1 - s_{b}\right) \] dairy breed bull calves,

\[ \tilde{N}_{XB} = N_{XB} \left(1 - s_{XB}\right) \] crossbred heifer calves, and

\[ \tilde{N}_{XB} = N_{XB} \left(1 - s_{XB}\right) \] crossbred bull calves

from cows that are alive after 14 d. The total number of dairy breed heifer calves thus equals \( \tilde{N}_c = \tilde{N}_c + \tilde{N}_c \). By assuming a rearing loss, \( r_{L} \), of 5% from Day 15 to Day 458, the farmer needs to raise \( \tilde{N}_{semp} = N_b / (1 - r_{L}) = 31.6 \) heifer calves. The others are sold at Day 14. The presumed sale proceeds \( \epsilon_{c} \), ... for purebred and crossbred calves are given in Table 4, while rearing costs of 40€ are assumed. From 1 January 2023, the minimum transport age in Germany was raised to 28 d. However, the calf market is still in a discovery phase, so prices for 14-d-old calves were used. The price differences between the sale proceeds and the rearing costs are denoted as \( \tilde{c}_{c} \), ... The farmer’s proceeds from the sale of calves thus equals

\[ \text{rev}_{calf} = \sum_{j \in \{c, h\}} \left( \tilde{N}_{c_j} \tilde{c}_{c} + \tilde{N}_{b_j} \tilde{c}_{b} + \tilde{N}_{XB_j} \tilde{c}_{XB} \right) - \tilde{N}_{semp} \tilde{c}_{c} \]

Model parameters were only considered permissible if at least as many dairy heifer calves were born as needed for replacement.

**Insemination Costs**

The insemination costs depend on the conception rates, which in turn depend on the type of semen that is used. Key parameters that depend on the semen type are summarized in Table 5. The presumed conception rate for heifers, \( \text{con}_h^u \), was 65%, and the conception rate for cows, \( \text{con}_c^u \), was 40% when unsexed semen was used. Sexed semen decreased the conception rate by 17%, in which case the conception rate for heifers, \( \text{con}_h^s \), was 54%, and the conception rate for cows, \( \text{con}_c^s \), was 33%.

It is assumed that in fertile cows, the number of inseminations per pregnancy follows a geometric distribution. Fertile cows should become pregnant with a probability, \( p^c_{preg} \), of 90%. The probability that a fertile cow is pregnant after a maximum of \( e_{sem}^c \) inseminations with unsexed semen equals \( p_{preg}^c = 1 - (1 - \text{con}_c^u)^{n_{sem}^c} \). Hence, the maximum permissible number of inseminations should be

\[ n_{sem}^c = \frac{\ln \left(1 - p_{preg}^c\right)}{\ln \left(1 - \text{con}_c^u\right)} = 4.5, \]

where \( \ln \) is the natural logarithm. Accordingly, the maximum number of inseminations with sexed semen should be \( n_{sem}^s = 5.7 \) for cows. Relevant for profit calculations is the insemination index, which is defined as the expected number of inseminations per cow in a lactation. The insemination index of fertile cows that are inseminated with unsexed semen equals...
\[
\Pi_{\text{cu fertile}} = \sum_{k=1}^{n_{\text{sem}}} k \left(1 - \text{con}_u\right)^{k-1} \text{con}_u + \left(1 - p_{\text{preg}}^c\right) n_{\text{sem}}^c
\]
\[
= 1 - \left(1 + n_{\text{sem}}^c \text{con}_u\right) \left(1 - \text{con}_u\right)^{n_{\text{sem}}^c} \frac{\text{con}_u}{1 - p_{\text{preg}}^c} + \left(1 - p_{\text{preg}}^c\right) n_{\text{sem}}^c
\]
\[
= 2.25.
\]

The second equality can be shown with the online math calculator eMathHelp (eMathHelp, 2022). Similarly, the expected number of inseminations with sexed semen, \(\Pi_{\text{cs fertile}}\), is 2.71. It is assumed that the cows that are being culled for diverse reasons have, on average, 30\% fewer inseminations than cows that are not being culled. The average number of inseminations per cow is thus
\[
\Pi_{\text{cs}} = N_{\text{insem}} \times \frac{\Pi_{\text{cs fertile}} + N_{\text{not preg}}^c n_{\text{sem}}^c + N_{\text{culled}}^c 0.7 \Pi_{\text{cs fertile}}}{N_{\text{insem}}}
\]
\[
= 2.10
\]
when unsexed semen is used, and \(\Pi_{\text{cs}} = 2.54\) when sexed semen is used. The corresponding values for heifers are computed accordingly. The insemination cost per year thus equals
\[
\text{cost}_{\text{semen}} = \sum_{j \in \{h,c\}} N_{\text{j}} \times \left(p_u^j \Pi_{\text{j}}^c \text{con}_u + p_p^j \Pi_{\text{j}}^c \text{con}_u + p_{\text{Bu}}^j \Pi_{\text{j}}^c \text{con}_u + p_{\text{Bs}}^j \Pi_{\text{j}}^c \text{con}_u\right)
\]
where the assumed costs \(\text{con}_u, \text{con}_c, \ldots\) per insemination are given in Table 5. These costs are average prices based on current price lists. They include semen costs, insemination costs, and the value-added tax.

**Genotyping Costs**

For the genotyping of a calf and the ear tag as part of a herd genotyping program, costs of approximately 27 € can be assumed. The actual price is higher if the farmer does not participate in a herd genotyping program. Provided that all \(N_{\text{g}}\) dairy-breed heifer calves are genotyped, additional costs of
\[
\text{cost}_{\text{geno}} = N_{\text{g}} \times 27
\]
arise per year.

**Genetic Gain**

Additional revenue from accelerated genetic gain arises from the superiority of the selected heifer calves.
over the selected heifer calves from the reference scenario. The average superiority of the heifer calves equals

\[ \Delta \bar{\mu}_{\text{calf}} = \bar{\mu}_{\text{calf}} - \bar{\mu}_{\text{calf}}^{\text{ref}}, \]

where \( \mu_{\text{calf}}^{\text{sel}} \) and \( \mu_{\text{calf}}^{\text{ref}} \) are the mean EBVs of the selected calves in the considered scenario and reference scenario, respectively. The scale of the breeding value is chosen such that a 1-unit increase in the true breeding value (TBV) is expected to reflect an increase of 1€ in net farm profit per cow per year. When selection decisions are based on the RZE, this is achieved by defining

\[ \bar{\mu}_{\text{calf}} = \mu_{\text{calf}}^{\text{sel}} / 3.04, \]

where \( \mu_{\text{calf}}^{\text{sel}} \) is the average RZE of the selected calves, and 3.04 is the average length of productive life that was assumed for the computation of the RZE.

The average length of productive life at the farm of interest equals \( PL = 1/p_{\text{rep}} = 3.33 \), so the superiority of the selected calves over the reference scenario equals \( \Delta \mu_{\text{calf}}^{\text{sel}} \cdot PL \), when measured over the whole length of productive life. The calves will pass half of their superiority to their offspring, a quarter to their grand offspring, and so on. As \( N_h \) heifers enter the farm each year, their cumulative contribution to the income of the farmer equals \( N_h \cdot PL \cdot \Delta \mu_{\text{calf}}^{\text{sel}} (1 + 0.5 + 0.25 + \ldots) \). To quantify what forecasted future earnings are worth today, future earnings must be discounted. For example, by assuming a discount rate of 7% per year and a generation interval of 4 years, the discount rate per generation, \( dr \), is 31%, and the discounted revenue from additional genetic gain is

\[ \Delta \text{rev}_{\text{gain}} = N_h \sum_{g=0}^{\infty} \frac{PL \cdot \Delta \mu_{\text{calf}}^{\text{sel}}}{(1 + dr)^{g+1}}. \]

Simplifying the equation provides

\[ \Delta \text{rev}_{\text{gain}} = N \Delta \mu_{\text{calf}}^{\text{sel}} / (1 + dr)^{1.25}. \]

Often, however, farmers are not interested in what the future earnings are worth today, but how high the cumulative additional revenue would be after one or 2 generations. In this case, the factor 1.25 at the right-hand side would be replaced by 1.0 or 1.5, respectively. The value 1.25 can then be seen as a compromise. The average RZE of the selected calves, \( \mu_{\text{calf}}^{\text{sel}} \), is derived in the following sections.

**Mean breeding value of the selected calves**

Different groups of heifers and cows contribute differently to the genetic gain. Cows inseminated with sexed and unsexed semen have different distributions of their EBVs, because sexed semen is used only on the genetically superior dams. Moreover, since genetic gain causes the heifers to be, on average, genetically superior to the cows, heifers and cows also have different distributions of their EBVs. The dams with dairy-breed offspring are, therefore, assigned to 4 classes that are handled separately:

- \((h, s)\): heifers inseminated with sexed semen,
- \((h, u)\): heifers inseminated with unsexed semen,
denote the proportion of dairy-breed heifer calves whose dams are heifers inseminated with sexed (unsexed) semen. Let \( \overline{p}_{cs} (\overline{p}_{cu}) \) denote the proportion of dairy-breed heifer calves whose dams are heifers inseminated with sexed (unsexed) semen. The EBVs of heifer calves from different classes have different distributions. Their means are denoted as \( \mu_{cs} (\mu_{cu}) \), \( \mu_{ca} \), \( \mu_{cs} \), \( \mu_{cu} \), and their variances are denoted as \( \sigma_{cs}^2 (\sigma_{cu}^2) \), \( \sigma_{ca}^2 \), \( \sigma_{cs}^2 \), \( \sigma_{cu}^2 \). Formulas for computing these means and variances are provided in the next section. The EBV of a randomly chosen heifer calf has a mixed distribution with weights \( \overline{p}_{hs}, \overline{p}_{hu}, \overline{p}_{cs}, \text{and} \overline{p}_{cu} \). Consequently, the EBV of the calf has mean

\[
\mu_{calf} = \overline{p}_{hs}\mu_{hs} + \overline{p}_{hu}\mu_{hu} + \overline{p}_{cs}\mu_{cs} + \overline{p}_{cu}\mu_{cu},
\]

while the variance \( \sigma_{calf}^2 \) can be computed with appendix Equation (1).

The mixture distribution is approximated by a normal distribution. There are, on average, \( \overline{N}_h \) dairy heifer calves born each year, from which \( \overline{N}_{calf} \) calves are raised for replacement. The proportion of heifer calves thus equals \( p_{calf} = \overline{N}_{calf} / \overline{N}_h \). Consequently, calves with an EBV larger than \( b_{calf} = -\mu_{calf} + \sigma_{calf} \Phi^{-1} (1 - p_{calf}) \) are kept for replacement breeding, where \( \Phi^{-1} \) is the quantile function of the standard normal distribution. The probability density function of the standard normal distribution is denoted as \( \phi \). The selection intensity within the purebred heifer calves equals

\[
\phi \left[ \Phi^{-1} (1 - p_{calf}) \right],
\]

so the average EBV of the selected calves is

\[
\mu_{calf} = \mu_{calf} + \sigma_{calf} \times \phi \left[ \Phi^{-1} (1 - p_{calf}) \right].
\]

**Breeding values of calves from different classes**

This section shows how the means \( \mu_{cs}, \mu_{cu}, \ldots \) and variances \( \sigma_{cs}^2, \sigma_{cu}^2, \ldots \) of the EBVs of calves from different classes depend on the means \( \mu_{cs}, \mu_{cu}, \ldots \) and variances \( \sigma_{cs}^2, \sigma_{cu}^2, \ldots \) of the EBVs of their dams.

The assumed values for quantitative genetic parameters are given in Table 6. The genetic standard deviation of the RZ€, \( \sigma_g \), which is defined as the standard deviation of the TBVs, equals 530 €. The mean reliability of heifer EBVs, \( r^2_h \), is 69% for genotyped heifers, and 19% for ungenotyped heifers. The mean reliability of cow EBVs, \( r^2_c \), is 75% for genotyped cows and 50% for ungenotyped cows.

The mean reliability of the EBVs of bulls, \( r^2_b \), is 69%. Bulls used for unsexed inseminations have EBVs with a mean, \( \mu_{bu}^{sel} \), of 2120 € and a standard deviation, \( \sigma_g^{sel} \), of 265 €. Bulls that are offered sexed are, on average, slightly older than the others, so they have lower EBVs. We assume, therefore, an average EBV, \( \mu_{bs}^{sel} \), of 1,855 € for these bulls, but the same standard deviation. Thus, bulls with unsexed semen are 4 genetic standard deviations above the base population, and bulls with sexed semen are 3.5 genetic standard deviations above the base.

For a group of animals that is selected based on their EBVs, the EBVs and TBVs have the same expectations but different variances. The variance of the TBVs is larger than the variance of the EBVs because of the random prediction error. The variance of the bull’s TBVs is \( \sigma_{b}^{sel^2} = \sigma_{b}^{sel^2} + (1 - r^2_h) \sigma_g^2 = 397 € \). The variances of the TBVs of the dams from each class are computed accordingly.

Farmers who do not participate in a herd genotyping program could select the heifer calves for replacement breeding based on the parent averages of the EBVs, in which case the EBVs of the calves from class \((c, u)\) have mean, \( \mu_{cu} \), and variance, \( \sigma_{cu}^2 \), equal to

\[
\mu_{cu} = \frac{\mu_{cu}^{sel} + \mu_{bu}^{sel}}{2},
\]

and

\[
\sigma_{cu}^2 = \frac{\sigma_{cu}^{sel^2} + \sigma_{b}^{sel^2}}{4},
\]

respectively. Participation in a herd genotyping program enables the farmer to account for the random deviation of the animal’s TBVs from the parent average. This deviation is called the Mendelian sampling deviation, which has mean 0 and variance \( \sigma_{c}^2 \). In this case, the EBVs of the calves from class \((c, u)\) have expectation \( \mu_{cu} = \mu_{cu}^{PA} \), but variance

\[
\sigma_{cu}^2 = \sigma_{c}^2 \left( \sigma_{cu}^{PA^2} + \frac{\sigma_{b}^{sel^2}}{2} \right),
\]

where
The EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBVs of the EBV...
being culled. For simplicity, we assumed $w_1 = w_2 = 0.5$ and $w_0 = 0$ otherwise, which is in accordance with the assumptions underlying the computation of the RZ€. The variance of the cow EBVs, $\sigma^2_{h}$, can be computed with Equation (1) from the appendix.

Dams for insemination with sexed dairy-breed semen are chosen from the upper tail of the respective breeding value distribution, so they are sampled from a one-sided truncated normal distribution. Dams for insemination with unsexed dairy-breed semen are chosen from its center, so they are sampled from a 2-sided truncated normal distribution. Heifers with an EBV larger than $h_{bc}$ are inseminated with sexed semen, and heifers with an EBV between $h_{cu}$ and $h_{bc}$ are inseminated with unsexed semen. The mixed distribution of the cow EBVs is approximated by a normal distribution with the same mean and variance. This provides the corresponding points of truncation, $a_c$ and $b_c$, for cows.

The means $\mu_{h_{cu}}$, $\mu_{h_{bc}}$, and standard deviations $\sigma_{h_{cu}}$, $\sigma_{h_{bc}}$ of the EBVs can then be computed with appendix Equation (2) for the dams that were inseminated with unsexed semen. Accordingly, the means $\mu_{h_{cu}}$, $\mu_{h_{bc}}$, and standard deviations $\sigma_{h_{cu}}$, $\sigma_{h_{bc}}$ of the EBVs can be computed with appendix Equation (3) for the dams that were inseminated with sexed semen.

**RESULTS**

The model was evaluated for different parameter settings and constraints. Table 7 shows the net benefit per cow for different constraint settings. All scenarios in this table assume that surplus heifer calves are sold for fattening. The asterisk marks the parameters that have been kept constant. The scenarios are compared with the reference scenario that assumes no herd genotyping and the sole use of unsexed Holstein semen.

The optimum scenario A1 generated 50.26 € more net profit per cow than the reference scenario. This increase in net profit was only partly achieved by herd genotyping, as herd genotyping alone would have increased the net profit by only 23.16 € (Scenario 4). In the optimum scenario A1, 49.6% of the heifers with the highest genetic merit were inseminated with female-sexed semen but also 11.3% of the cows with the highest genetic merit. This practice increased the TBVs of the purebred heifer calves, which led to additional revenue due to an accelerated genetic gain of 43.15 €. It also enabled the cows and heifers with the lowest EBVs to be inseminated with beef breed semen, which led to an additional revenue from the sale of calves of 23.75 €. Using unsexed beef breed semen always resulted in greater net profit than using male-sexed beef breed semen, which was due to the small price difference between crossbred heifer calves and crossbred bull calves.

The insemination of heifers with semen from beef breeds such as Belgian Blue may lead to high stillbirth rates. Therefore, we also considered an alternative scenario in which inseminating heifers with beef breed semen was forbidden (Scenario A3). This restriction decreased the net profit only marginally by 1.49 € per cow. Scenario A3 also shows that inseminating 10.3% of the cows with the highest genetic merit with female-sexed semen was optimal. Not using sexed semen on cows would slightly reduce the net profit by 3.08 € per cow (Scenario A4).

Without herd genotyping, the farmer could increase the net profit by not more than 29.61 € per cow (Scenario A2). This increase would mainly be achieved by increasing the revenue from the sale of calves. Relatively little genetic gain could be achieved because selecting heifer calves for replacement breeding would be based on the pedigree-based EBVs, which almost does not allow breeders to utilize the Mendelian sampling variance. As a consequence, the optimum was achieved when as many dairy-breed heifer calves were born as needed for replacement. The typically lower EBVs of dairy breed bulls used for sexed inseminations caused the selected calves to have, on average, lower EBVs than in the reference scenario.

The scenarios in Table 8 all assume that beef-breed semen is not used on heifers. Scenario A3 assumed that surplus Holstein heifer calves are sold for fattening. However, if a farmer implements the optimum insemination strategy, then the farmer would probably soon be able to sell the surplus Holstein heifer calves for replacement, in which case the farmer could expect a revenue of approximately 200 € instead of 30 € per heifer calf. Scenario A3* shows the optimum insemination strategy for this farmer. As this farmer can obtain higher prices for the heifer calves, it is advantageous for him to inseminate a larger proportion of the dams with female-sexed Holstein semen.

To determine whether herd genotyping would still be beneficial if selection decisions were based on a less suitable selection index, we determined the minimum genetic standard deviation for which herd genotyping is beneficial. Scenarios B1 and B2 show that the minimum genetic standard deviation is 270€. In this case, the additional revenue from accelerated genetic gain would exceed the genotyping costs only slightly, and additional net profit relative to the reference scenario would primarily be generated from the sale of calves.

Figure 1 shows the maximum achievable increase in the net profit per cow when the proportion of the herd that is inseminated with female-sexed Holstein semen...
is constrained to a certain value. The optimum proportion of the herd that should be inseminated with female-sexed Holstein semen was between 10% and 30% depending on the replacement rate. The lower the replacement rate is, the higher the achievable increase in net profit by herd genotyping and optimized semen allocation is. The high increase in net profit for herds with low replacement rates arises because of the higher selection intensity for heifer calves, because the selected replacement heifers can show their genetic superiority over a longer period of time, and because a higher proportion of cows with low EBVs can be inseminated with beef breed semen. However, care must be taken given that the breeding value RZ€ was computed for an average herd and might not provide accurate predictions for herds with extreme replacement rates. Note that the lines corresponding to different replacement rates refer to different reference scenarios, so the figure does not show whether low replacement rates are beneficial to a farmer.

**DISCUSSION**

A deterministic model was introduced that predicts the net benefit per cow resulting from participation in a herd genotyping program and from using sexed semen and beef breed semen. The model was evaluated with the example of a German Holstein farm, but it can easily be adapted to other dairy breeds and other countries, provided that the farming system does not rely on a fixed calving interval of one year.

Taking part in a herd genotyping program was shown to be beneficial for German Holstein farms. Herd genotyping enables the farmer to get accurate EBVs for purebred heifer calves at an early age. GEBVs can be used not only for identifying calves for replacement breeding but also for identifying genetically superior cows and heifers that are suitable for insemination with female-sexed Holstein semen and for identifying genetically inferior females that are suitable for insemination with beef breed semen. The use of female-sexed semen on the genetically superior cows enables an increase in genetic gain by increasing the average EBV of the heifer calves and by increasing the number of calves from which the replacement heifers are selected. The use of female-sexed semen, however, has a decreasing marginal utility. Using beef breed semen on the cows with the lowest EBVs was, therefore, often beneficial, as it increased the proceeds from the sale of calves.

The current small price difference between crossbred bull and heifer calves that was assumed in our study made the use of male-sexed semen from beef breeds noneconomic. Particularly for heifers, it is important to use only beef breed bulls with excellent EBVs for easy births so that the high stillbirth rates that were assumed in this study are not realized. The optimum scenario allocated a small proportion of beef breed semen to heifers, which could be considered an animal welfare issue. As not using beef breed semen in heifers reduced the net benefit only marginally, it can be recommended to use beef breed semen only for cows. In that case, the optimum strategy for semen allocation involved using female-sexed Holstein semen on 49% of

### Table 7: Comparison of net benefit per cow for different scenarios

<table>
<thead>
<tr>
<th>Age class</th>
<th>Sire breed</th>
<th>Semen type</th>
<th>Scenario</th>
<th>UnitRef.</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
<th>A5</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herd genotyping3</td>
<td>Holstein</td>
<td>unsexed</td>
<td>o</td>
<td>x</td>
<td>100.0</td>
<td>38.4</td>
<td>69.1</td>
<td>51.5</td>
<td>46.4</td>
<td>100.0</td>
</tr>
<tr>
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<td>Holstein</td>
<td>female-sexed</td>
<td>0.0</td>
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<td>53.6</td>
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<td>0.0</td>
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<tr>
<td>Heifers</td>
<td>Beef breed</td>
<td>unsexed</td>
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<td>12.0</td>
<td>5.7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Heifers</td>
<td>Beef breed</td>
<td>male-sexed</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Cows</td>
<td>Holstein</td>
<td>unsexed</td>
<td>100.0</td>
<td>51.7</td>
<td>49.0</td>
<td>50.9</td>
<td>65.5</td>
<td>100.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Cows</td>
<td>Holstein</td>
<td>female-sexed</td>
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<td>11.3</td>
<td>4.6</td>
<td>10.3</td>
<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
</tr>
<tr>
<td>Cows</td>
<td>Beef breed</td>
<td>unsexed</td>
<td>0.0</td>
<td>37.1</td>
<td>46.4</td>
<td>38.8</td>
<td>34.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Cows</td>
<td>Beef breed</td>
<td>male-sexed</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Revenue from sale of calves (rev\textsubscript{calf})</td>
<td>0.0</td>
<td>23.75</td>
<td>30.27</td>
<td>21.40</td>
<td>19.53</td>
<td>0.0</td>
<td>€</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Insemination costs (\textsubscript{costsemen})</td>
<td>0.0</td>
<td>−6.45</td>
<td>2.93</td>
<td>−5.94</td>
<td>−1.23</td>
<td>0.0</td>
<td>€</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Genotyping costs (\textsubscript{costgeno})</td>
<td>0.0</td>
<td>−10.19</td>
<td>0.00</td>
<td>−10.42</td>
<td>−10.28</td>
<td>−11.28</td>
<td>€</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revenue from genetic gain (\textsubscript{revgain})</td>
<td>0.0</td>
<td>43.15</td>
<td>−3.58</td>
<td>43.78</td>
<td>37.67</td>
<td>34.44</td>
<td>€</td>
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</tr>
<tr>
<td>Total</td>
<td>0.0</td>
<td>50.26</td>
<td>29.61</td>
<td>48.77</td>
<td>45.69</td>
<td>23.16</td>
<td>€</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1The scenarios differ by the parameters that have been set to fixed values. All scenarios are compared with a reference scenario that assumes no herd genotyping and the sole use of unsexed Holstein semen.
2The reference scenario.
3'x' means that the herd was genotyped, while 'o' means that the herd was not genotyped.
4\text{Total} = \text{rev\textsubscript{calf}} + \text{\textsubscript{costsemen}} + \text{\textsubscript{costgeno}} + \text{\textsubscript{revgain}}.

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Journal of Dairy Science Vol. TBC No. TBC, TBC
the heifers with the highest genetic merit and on 10% of the cows with the highest genetic merit, while 39% of the genetically inferior cows would be inseminated with unsexed beef breed semen. The optimum proportions, however, are sensitive to farm-specific peculiarities. In all considered scenarios, the additional breeding progress and the higher calf prices that can be achieved through the optimal strategy more than compensated for the cost of herd genotyping.

The optimum allocation of semen to cows and heifers on dairy farms and participation in a herd genotyping program are issues that have been repeatedly discussed in the literature but with mixed results (McCullock et al., 2013; Cottle et al., 2018; Ettema et al., 2017; Newton et al., 2018). The variety of results is partly due to their sensitivity to farm-specific peculiarities. In particular, profitability was found to be very sensitive to the price of dairy heifer calves (McCullock et al., 2013). Therefore, we developed a deterministic model for the computation of the farmer’s expected net benefit and implemented it in an Excel spreadsheet that can be completed by the farmers. The spreadsheet optimally allocates different types of semen to heifers and cows depending on their EBVs and computes the net benefit of the farmer relative to a reference scenario.

The model assumed that the farmer pursues an extended lactation strategy. That is, the intended calving interval at the farm is assumed to be sufficiently long that the farmer is able to set the start of insemination earlier when semen with low fertilization capacity is used. If the heat of the cow is reliably detected, then inseminations with sexed semen should start approximately 10 d earlier than inseminations with unsexed semen to maintain the intended calving interval on average. The 10 d were obtained from the insemination indices as \((2.54 - 2.10)\times 21 \text{ d} \approx 10 \text{ d}\). The economic assessment of extending the calving interval of high-yielding cows is controversial. Some authors see benefits (Harms et al., 2021), while others found that an extended lactation strategy can give the same economic return as a traditional lactation period (Sehested et al., 2019). Niozas et al. (2019) concluded that the extension of the voluntary waiting period of high-yielding cows up to 120 d has no adverse effects regarding milk production, involuntary culling, udder health, or body condition score gain. Prolonging the lactation period has the effects that the cows spend less of their time in a state of energy deficiency, and that fewer calves are born per kg of milk produced. The latter has a long-term positive impact on the value of fattening calves and the profitability of crossbreeding.

The model was evaluated with the example of the German selection index RZE, which has a relatively high genetic standard deviation of 530€. The reasons for the relatively large genetic standard deviation are that the RZE was specifically designed to predict the economic superiority of a cow and that the RZE incorporates a large number of economically relevant health traits. In addition to performance traits and productive life, the RZE also incorporates breeding values for mastitis, 6 different claw disorders, estrus cycle disorder, metritis, retention of the placenta, abomasum displacement, milk fever, ketosis, interval from birth to first insemination, interval from first to successful

### Table 8: Net benefit per cow for scenarios with different settings for the fixed parameters

<table>
<thead>
<tr>
<th>Age class</th>
<th>Sire breed</th>
<th>Semen type</th>
<th>Scenario</th>
<th>A3</th>
<th>A3*</th>
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<th>B2</th>
<th>Unit</th>
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<tr>
<td>Heifers</td>
<td>Holstein</td>
<td>unsexed</td>
<td></td>
<td>30.00</td>
<td>200.00</td>
<td>30.00</td>
<td>30.00</td>
<td>€</td>
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<td>female-sexed</td>
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<td>€</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>o</td>
<td>%</td>
</tr>
<tr>
<td>Heifers</td>
<td>Beef breed</td>
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<td></td>
<td>51.5</td>
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<td>50.4</td>
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<tr>
<td>Cows</td>
<td>Holstein</td>
<td>unsexed</td>
<td></td>
<td>48.5</td>
<td>71.0</td>
<td>49.6</td>
<td>41.6</td>
<td>%</td>
</tr>
<tr>
<td>Cows</td>
<td>Holstein</td>
<td>female-sexed</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>%</td>
</tr>
<tr>
<td>Cows</td>
<td>Beef breed</td>
<td>unsexed</td>
<td></td>
<td>10.3</td>
<td>16.4</td>
<td>5.2</td>
<td>2.4</td>
<td>%</td>
</tr>
<tr>
<td>Cows</td>
<td>Beef breed</td>
<td>male-sexed</td>
<td></td>
<td>50.9</td>
<td>58.9</td>
<td>42.4</td>
<td>42.8</td>
<td>%</td>
</tr>
<tr>
<td>Cows</td>
<td>Beef breed</td>
<td>male-sexed</td>
<td></td>
<td>38.8</td>
<td>24.7</td>
<td>52.4</td>
<td>54.8</td>
<td>%</td>
</tr>
<tr>
<td>Revenue from sale of calves (rev\text{calf})</td>
<td></td>
<td></td>
<td></td>
<td>21.40</td>
<td>17.76</td>
<td>30.98</td>
<td>33.37</td>
<td>€</td>
</tr>
<tr>
<td>Insemination costs (cost\text{semen})</td>
<td></td>
<td></td>
<td></td>
<td>−5.94</td>
<td>−15.98</td>
<td>−0.18</td>
<td>3.23</td>
<td>€</td>
</tr>
<tr>
<td>Genotyping costs (cost\text{geno})</td>
<td></td>
<td></td>
<td></td>
<td>−10.42</td>
<td>−12.52</td>
<td>−9.11</td>
<td>0.00</td>
<td>€</td>
</tr>
<tr>
<td>Revenue from genetic gain (rev\text{gain})</td>
<td></td>
<td></td>
<td></td>
<td>43.73</td>
<td>59.73</td>
<td>10.45</td>
<td>−4.55</td>
<td>€</td>
</tr>
<tr>
<td>Total3</td>
<td></td>
<td></td>
<td></td>
<td>48.77</td>
<td>48.98</td>
<td>32.14</td>
<td>32.04</td>
<td>€</td>
</tr>
</tbody>
</table>

1 All scenarios assume that beef breed semen is not used for heifers. Each scenario is compared with the corresponding reference scenario that assumes no herd genotyping and the sole use of unsexed Holstein semen.
2 ‘x’ means that the herd was genotyped, while ‘o’ means that the herd was not genotyped.
3 Total = \(\text{rev\text{calf}} + \text{cost\text{semen}} + \text{cost\text{geno}} + \text{rev\text{gain}}\).
insemination, stillbirth rates, calving ease, and rearing losses. The incorporation of direct health traits allows the RZ€ to account for veterinary treatment costs. This selection index can thus explain a larger proportion of the genetic variance in the animal’s true economic value than previously used German selection indices. For comparison, the standard deviation of the true transmitting ability for the American Lifetime Net Merit (NM$) is $234 (VanRaden et al., 2021), which corresponds to a genetic standard deviation of $468 or 435€, where $1 = 0.93€ (http://www.xe.com/currencyconverter/; accessed February 2023). If selection is based on a breeding value that is not expressed in monetary terms, then a regression of the RZ€ on that breeding value provides an appropriate scaling factor with which the EBVs can be multiplied. For example, regression of the RZ€ on the RZG in a random sample of genotyped heifer calves showed that the appropriate scaling factor for the RZG equals 43.06 (not shown elsewhere).

The present study revealed that herd genotyping and using sexed semen and beef breed semen on a portion of the cows is economically beneficial. The recommendations made by other authors are diverse. Some early papers argued that herd genotyping cannot often be justified when the genotyping costs are AU$50 per cow (Pryce and Hayes, 2012) because selection based on the parent average could compete with that strategy. This recommendation, however, relied on the assumption that the reliability of selection equals the model-based reliability of the parent average, which led to an overestimation of the genetic progress (Bijma, 2012). The reduction in reliability of selection relative to the model-based reliability is much less pronounced for GE-BVs (Gorjanc et al., 2015). Consequently, Calus et al. (2015) concluded that the benefits of selection based on genomic strategies over pedigree-based strategies were likely underestimated in early papers. In our model, we calculated the variance of the estimated parent average directly from the variances of the parental EBVs, so the accuracy of the parent average was not needed for the calculations. We accounted for a reduced genetic variance by introducing the parameter η that quantifies the reduction of the variance of the EBVs in the parents due to selection and compensatory matings. Compensatory mating is a strategy for producing animals with more homogeneous trait characteristics (Ferreira, 2021).

Newton et al. (2018) concluded that genomic testing alone was always more profitable than using sexed semen and genomic testing together, provided that the only benefit considered was increased genetic gain in heifer replacements. This conclusion is not aligned with our results, but this apparent contradiction can

Figure 1. The maximum achievable increase in the net profit per cow over the reference scenario is shown when the percentage of the herd that is inseminated with female-sexed Holstein semen is constrained to a certain value. The increase in net profit is shown for different replacement rates. Only the cows and heifers with the highest breeding value are inseminated with female-sexed semen.
be resolved as follows. First, Newton et al. (2018) assumed that a random sample of heifers was inseminated with female-sexed semen, while we assume that the genetically superior ones are used. Using only the superior ones increased the average EBV of the selected offspring, which led to an additional benefit for the farmer. Second, using female-sexed dairy breed semen for the genetically superior dams resulted in offspring of genetically inferior cows not needed for replacement breeding. The inferior cows could thus be inseminated with cheaper beef breed semen, which also led to additional revenue from the sale of calves. Third, Newton et al. (2018) and most other authors computed only the benefit that can be generated by the offspring itself during its lifetime. However, the animals will pass half of their genetic superiority on to their offspring, a quarter to their grand offspring, and so on. We also accounted for future generations and discounted future earnings. Finally, Newton et al. (2018) performed the calculations for a different farming system: a pasture-based system with seasonal calving.

The use of beef breed semen with genetically inferior cows turned out to be beneficial in our analysis, so it can be expected that crossbreeding with beef cattle breeds will increasingly take place on German Holstein farms. The beef traits of crossbred offspring should, therefore, be included as additional traits in the total merit index for Holsteins. Genetic gain in these traits could not only increase the value of crossbred calves that are sold for fattening but also the value of cows that are being culled.

The recommendations made by the model do not apply to elite farms, as elite farms generate additional income by selling male breeding animals, which was not considered here. In addition, for maintaining biosecurity, it makes sense to rear slightly more than the required number of heifers. This helps in the avoidance of both the need to purchase heifers and the introduction of pathogens.

CONCLUSION

Participation in herd genotyping programs is profitable for Holstein breeders. In all considered scenarios, the additional breeding progress and the higher calf prices that can be achieved through the optimal allocation of different types of semen to cows and heifers more than compensated for the cost of herd genotyping. The genetically superior cows and heifers should be inseminated with female-sexed Holstein semen, while the genetically inferior cows should be inseminated with unsexed beef breed semen. The optimum proportions depend on farm-specific peculiarities.

AUTHOR CONTRIBUTIONS

R. W. developed the statistical model, wrote the article and designed the Excel spreadsheet. A. R. determined the values of the economic parameters. S. R. helped to improve the model and to gather genetic parameters. J.B. supervised the project.

Competing interests The authors declare that they have no competing interests.

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APPENDIX

Mixture Distribution

Let \( X \) denote a random variable from a mixture distribution of \( n \) one-dimensional component distributions with weights \( w_i \), means \( \mu_i \), and variances \( \sigma_i^2 \). Then, the mean and variance of \( X \) are (Frühwirth-Schnatter, 2006):

\[
E(X) = \mu = \sum_{i=1}^{n} w_i \mu_i,
\]

\[
\text{Var}(X) = \sum_{i=1}^{n} w_i \left( \sigma_i^2 + \mu_i^2 \right) - \mu^2.
\]  

One-Sided Truncated Normal Distribution

Let \( X \sim N(\mu, \sigma^2) \) be a normally distributed random variable with mean \( \mu \) and variance \( \sigma^2 \). Suppose that \( X \) lies in the interval \((a, \infty)\). Then, \( X \) conditional on \( X > b \) has a truncated normal distribution with mean and variance

\[
E(X|X > b) = \mu + \sigma \frac{\phi(\beta)}{1 - \Phi(\beta)},
\]

\[
\text{Var}(X|X > b) = \sigma^2 \left[ 1 + \frac{\beta \phi(\beta)}{1 - \Phi(\beta)} - \left( \frac{\phi(\beta)}{1 - \Phi(\beta)} \right)^2 \right].
\]  

Two-Sided Truncated Normal Distribution

Let \( X \sim N(\mu, \sigma^2) \) be a normally distributed random variable with mean \( \mu \) and variance \( \sigma^2 \). Suppose that \( X \) lies in the interval \((a, b)\). Then, \( X \) conditional on \( a < X < b \) has a truncated normal distribution with mean and variance (Johnson et al., 1994):

\[
E(X|a < X < b) = \mu - \sigma \frac{\phi(\beta) - \phi(\alpha)}{\Phi(\beta) - \Phi(\alpha)},
\]

\[
\text{Var}(X|a < X < b) = \sigma^2 \left[ 1 - \frac{\beta \phi(\beta) - \alpha \phi(\alpha)}{\Phi(\beta) - \Phi(\alpha)} \right].
\]