Exploring heifer fertility, sire selection, and herd survival analyses in herds with automated data capture

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Abstract
Globally, dairy producers face growing pressures to boost production while maintaining animal welfare and longevity. In response, many are adopting precision management technologies for detailed data acquisition. This trend is evident in South Africa, where dairy managers increasingly use Automated Milking Systems (AMS), integrating hardware and software to collect real-time production, fertility, and health data. These systems enable tailored herd management strategies. This study evaluated the efficacy of AMS herd management software on a total mixed ration (TMR) and a pasture-based dairy farm in South Africa. Historical herd performance data were analyzed, focusing on heifer fertility, sire rankings, and survivability. Key differences emerged between systems: 36% of heifers calved between 25-26 months in the TMR herd, while 53.5% of pasture-based heifers calved at 22-24 months. Time-trend analysis revealed a declining Age at First Calving (AFC) across both systems, highlighting improvements in heifer rearing and fertility management. Progeny performance analyses strongly correlated sires and offspring survivability (TMR: $R^2 = 0.91$, Pasture: $R^2 = 0.97$), emphasizing AMS software's role in sire selection. However, survivability declined with successive lactations, with the highest exits occurring between the heifer phase and third lactation (Pasture: 75%; TMR: 83%). These findings demonstrate the critical role of management software in recording historic fertility data, progeny performance, and survivability in South African dairy herds.

Keywords: Afifarm software, heifer management, progeny records, longevity
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Introduction
The anticipated surge in global demand for dairy products necessitates a threefold increase in dairy production by 2050 compared to 2003 (Meissner *et al*., 2023). Achieving this ambitious goal hinges upon optimizing production while prioritizing fertility and animal welfare to ensure sustainability (Dallago *et al*., 2021; Shalloo *et al*., 2021). Technology emerges as a pivotal ally in this endeavor, albeit with a caveat: its responsible deployment, especially within high-producing herds, is paramount.

Automated milking systems (AMS) is a technological leap forward tailored to enhance dairy animal monitoring and management (Gaworski, 2021). The evolution of technology in dairy production spans over 150 years (Groher *et al*., 2020), with automated systems making their debut in the early 1990s (Ozella *et al*., 2023). Their widespread adoption, notably in regions like Europe, Canada, North America, Australia, and New Zealand (Cogato *et al*., 2021; Henchion *et al*., 2022), underscores a global trend supported by escalating herd sizes and the quest for digitalized management to ensure economic sustainability (Simitzis *et al*., 2021).

Automated data capture encompasses a plethora of technologies (Markov *et al*., 2022), ranging from machine milking to RFID tags, in-line milk meters, pedometers, tri-axial accelerometers, and automatic weighing and feeding systems, among others. Algorithms harness data from these sensors to monitor performance metrics and flag potential health and welfare issues such as acidosis, mastitis, lameness, anestrus, metritis, and hypocalcemia (Singh *et al*., 2021; Agrawal *et al*., 2023). Adoption rates of these technologies vary across farms, contingent upon factors like farm size, milking parlour design, and the desire to reduce labour dependency (Yang *et al*., 2021).

Furthermore, AMS management software records crucial reproductive dates and events, such as insemination and calving dates, facilitating effective individual and contemporary fertility management strategies (Giordano *et al*., 2022; Kleen & Guatteo, 2023). Managers also have the option to record the dam's herd number and the sire's registration number on the system for comprehensive pedigree records.

Interval traits like Age at First Calving (AFC) and Inter Calving Period (ICP) serve as primary fertility indicators, analyzed at both the herd and individual animal levels using digitalized fertility records. These traits are managed with automated oestrus detection based on activity budget variation, enabling timely insemination by identifying and sorting heifers and cows on heat (Piwczyński *et al*., 2020; Tippenhauer *et al*., 2021; Das *et al*., 2023).

Heifer rearing and fertility management constitute the basis of a sustainable dairy herd. Replacement heifers entering the milking herd play a pivotal role in sustaining milk production continuity and elevating the genetic potential for production and fertility. Sustaining heifers on a post-weaning growth trajectory is paramount for ensuring prompt conception and maintenance of gestation (Kusaka *et al*., 2022). Atashi *et al*. (2021) highlight the significance of managing heifers to achieve an AFC within the range of 24 to 26 months for optimal lifetime performance.

This age window not only optimizes milk production but also mitigates risks such as dystocia, maintains low somatic cell counts (SCC), and shortens the ICP of subsequent lactations. Further insights from Kusaka *et al*. (2023) underscore the correlation between AFC and survivability, advocating for heifers to calve between 22 and 24 months. This balance between early calving and ensuring heifer maturity is vital for sustained lactation and herd resilience. Heifer management technology that facilitates precise body weight and oestrus detection for timely insemination is indispensable for fostering resilience and longevity in dairy herds (Bianchi *et al*., 2022).

The national dairy herd (dry and lactating cows) in South Africa totals 506 268 thousand cows (Milk SA, 2024), with an estimated 65% managed by automated technology (Gresse, 2018). Technology plays a crucial role in supporting South African producers with large herds, by enabling the tracking of individual animal parameters and recording herd performance over time. However, the adoption of digital dairy recording software on farms may contribute to the low participation rate of cows in national milk recording, estimated to be less than 10% (SA Stud Book http://www.sastudbook.co.za/ p116/services/logix-milk.html).

Producers rely on comprehensive on-farm software platforms to serve as data repositories for consultation and benchmarking. Dairy experts proficient in extracting performance data from these platforms provide analyses and feedback reports to support herd management. Leading dairy technology companies in South Africa include Afimilk, Delaval, and GEA, which offer aftermarket functions for data analyses and consultation (Gresse, 2018). Integrative management models are an attractive future option for the South African dairy industry. Based on present and historic data analyses, future herd performance trends and economic feasibility can be anticipated. Gargiulo *et al*., (2022) reported that predictive modelling is possible from automated herd data where farmers found the model user-friendly and valuable for managing herds towards an optimal future economic scenario. However, their model requires a large reference population to be accurately calibrated.

The objective of this study was to explore the functionalities of the Afifarm herd management software from Afimilk for extracting historical herd performance data with reference to heifer fertility, lifetime performance, and Artificial Insemination (AI) sire records for a pasture-based and total mixed ration (TMR) dairy herd in South Africa.

Materials and methods

Two dairy producers employing a TMR and pasture system, respectively, granted consent to extract and analyze their herd performance records. Both producers utilized the Afifarm herd management system, provided by Afimilk, which facilitated the collection of comprehensive herd performance data during researcher visits to the farms. Ethical clearance for utilizing external data was obtained from the Faculty of Natural and Agricultural Science ethics committee at the University of Pretoria (EC161209-0890).

Pasture-based herd

The data from the pasture-based farm originated from a herd of approximately 1700 cows and heifers, predominantly comprised of Holsteins and Holstein x Jersey crossbreeds. Before adopting the Afimilk system in 2005, Agrimilk management software was utilized. Data for animals enrolled in Agrimilk was transferred to Afimilk, enabling extraction of pre-2005 data. A 64-point rotary system, integrated with Afifarm herd management software version 4.1, was installed in 2005. Operations were conducted in two daily intervals: 04:30-08:30 and 14:30-17:30.

Animals were pasture-fed, supplemented with a concentrate ration in the milking parlor via the Afifeed system. Newborn calves were individually housed, receiving colostrum for the first two days, followed by a mixture of whole milk and milk-replacer twice daily. Starter pellets were introduced ad libitum from day three, with weaning completed by three months. Regular weighing every two weeks ensured adherence to growth targets. Heifers grazed on pasture after weaning, supplemented with protein-rich roughage, mainly Alfalfa hay. At 13 months, heifers were tagged with pedometers and introduced to the milking parlour for weight and activity software monitoring after the morning milking session. Those meeting the desired weight and body condition criteria, along with signs of heat, were flagged for insemination with semen sourced from reputable international AI companies. This producer's breeding objectives focused on body conformation, fertility, longevity, and milk production. If necessary, heat detection was augmented by observing activity spikes, followed by manual confirmation and re-insemination. Cows not exhibiting subsequent signs of heat underwent pregnancy diagnosis approximately 42 days post-AI by a veterinarian.

TMR herd

The data for the Holstein herd originated from approximately 4000 Holstein cows and heifers, milked thrice daily with the Afimilk system installed in 2002. The Afifarm herd management software version 3.076 was installed in the parlour. A 64-point rotary system was added in 2005, equipped with fans to mitigate heat stress. Animals were housed in roofed units with a deep litter system and received a specialized diet. Newborn calves were housed in individual hutches, receiving colostrum and transitioning to milk replacer by day five, and weaned by two months of age. Semen for AI primarily originated from the USA, Canada, and Europe. This producer's breeding objectives focused on udder conformation and health, high milk production and fertility.

Heifers were tagged and equipped with pedometers between 13 and 15 months of age. Those exhibiting heightened activity levels were inspected for heat and inseminated accordingly. Subsequent heat signs prompted re-insemination, while pregnancy was confirmed approximately 44 days post-insemination by a veterinarian.

Data Extraction from Afifarm

Historical performance data for animals registered on the Afifarm software was extracted. This was achieved by creating software backups, archived from both Afifarm systems. Following the researcher's installation of Afifarm versions 3.076 and 4.1, both backups were successfully reinstated to access data. Extensive fertility records were considered for historic trend analyses for all animals registered on the system between 2002 and 2014 in the TMR herd and 2002 to 2015 in the pasture-based herd.

Data reports were generated to extract a list of heifer herd numbers within their birth year. To be considered in the reports, heifers had to have at least one calving event. There were 3222 complete heifer records for the pasture-based herd and 8211 records for the TMR herd. The reports were then populated with insemination and calving dates for heifers within their birth years, and subsequently utilized to establish AFC values for all recorded heifers.

A cull-report was generated to establish the days in the system and the lactation number at exit. The pasture-based report had 2551 exits over the study period, and the TMR herd report had 6664 exits. Furthermore, sire records were extracted alongside progeny production reports and exit dates, detailing AI sire numbers matched with respective progeny data. Lifetime performance metrics were then calculated from the data, including days in the system and total daily milk yield days in the system for all progeny. Sires were ranked based on the mean days their progeny spent in the system. Sires with a minimum of 40 daughters were considered for analyses. The pasture-based herd delivered 40 bulls with 2464 progeny (mean: 62 daughters/bull), while the TMR herd delivered 95 bulls with a total progeny number of 5390 (mean: 57 daughters/bull).

Data Analyses

Data reports from Afifarm were exported to Microsoft Excel for storage and editing. Statistical analyses were conducted using GenStat 18th edition software (GenStat®, Payne, 2015). For AFC analysis, means were stratified within heifer birth year and compared using Fisher's protected least significant difference test at the 5% level of significance, as outlined by Snedecor & Cochran (1980).

To illustrate the correlation between longevity and lifetime efficiency, linear regression analyses were performed for sires ranked based on the mean days in the system of their progeny, incorporating milk yield per day in the system. Additionally, the frequency distribution of lactation number at exit was examined for both herds from the cull reports, serving as an indicator of survivability within each population.

Results

The Afifarm software proved highly efficient and comprehensive in extracting data tables. The volume of available data points was proportional to herd size (Table 1), ensuring sufficient data for conducting robust analyses and identifying meaningful trends.

Table 1 Descriptive statistics for parameters extracted from Afifarm

	n	Mean	Standard deviation
AFC			
Pasture-based	3222	24	1.7
TMR	8211	25.7	2.7
**AI Sires: days in the system*			
Pasture-based	40	1532	319
TMR	95	1395	466
**AI Sires: milk yield (kg)/days in the system*			
Pasture-based	40	9	2.4
TMR	95	12	5
Lactation number at the exit date			
Pasture-based	2551	2.4	1.7
TMR	6664	2	1.6

*The mean was established from the progeny data collected for each individual Artificial Insemination (AI) sire.

In this study, AFC served as a key metric for evaluating heifer rearing and fertility management. Analysis of AFC frequency in the pasture-based herd (Figure 1) revealed a predominant clustering of heifer calving within the desirable range of 22 to 24 months**.**

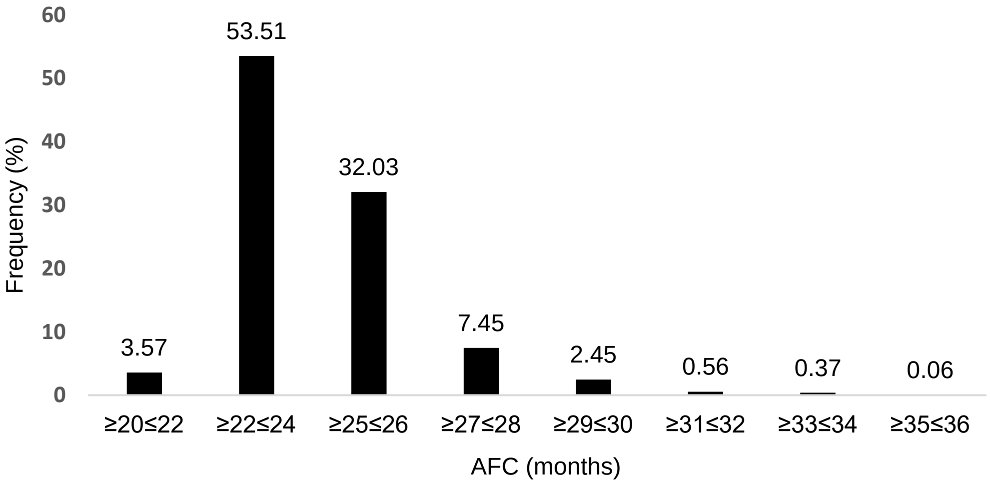

Figure 1 AFC distribution in the pasture-based herd

Conversely, the TMR herd displayed a bell-shaped distribution of AFC across various age brackets (Figure 2), indicating a notable contrast between the two systems, with the majority of heifers calving at 25 months or older.

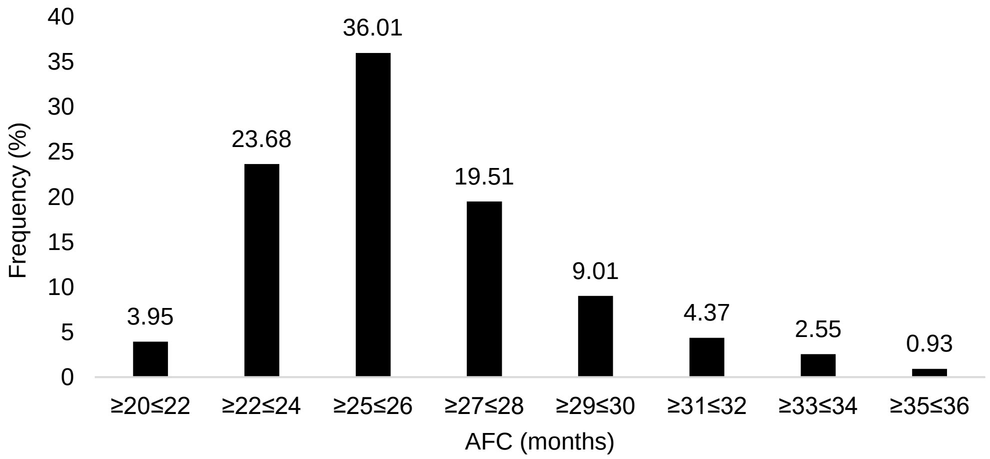

Figure 2 AFC distribution in the TMR herd

In the pasture-based herd, the mean AFC exhibited less variation between birth years, although a downward trend (P > 0.05) was evident from 2002 to 2015 (Figure 3). A notable spike in AFC occurred in 2004 and 2005 compared to the preceding and following years. However, from 2006 onward, improvements in heifer fertility management likely led to better AFC results.

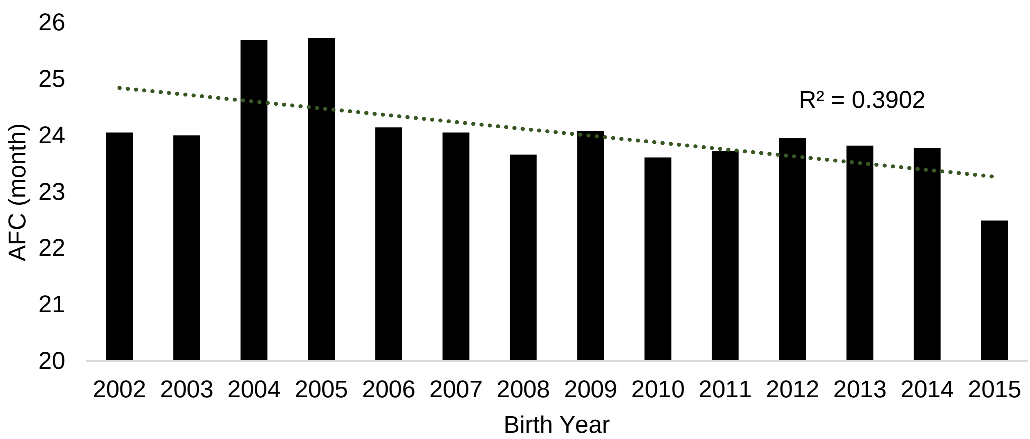

Figure 3 AFC Trend analyses in the pasture-based herd

In the TMR herd, there was a gradual increase (P > 0.05) in AFC from 2002 to 2006 (Figure 4). However, starting from 2007, a downward trend emerged, indicating a strong emphasis on reducing the mean AFC in the herd. This trend could be attributed to the implementation of improved pre-pubertal and automated fertility management practices.

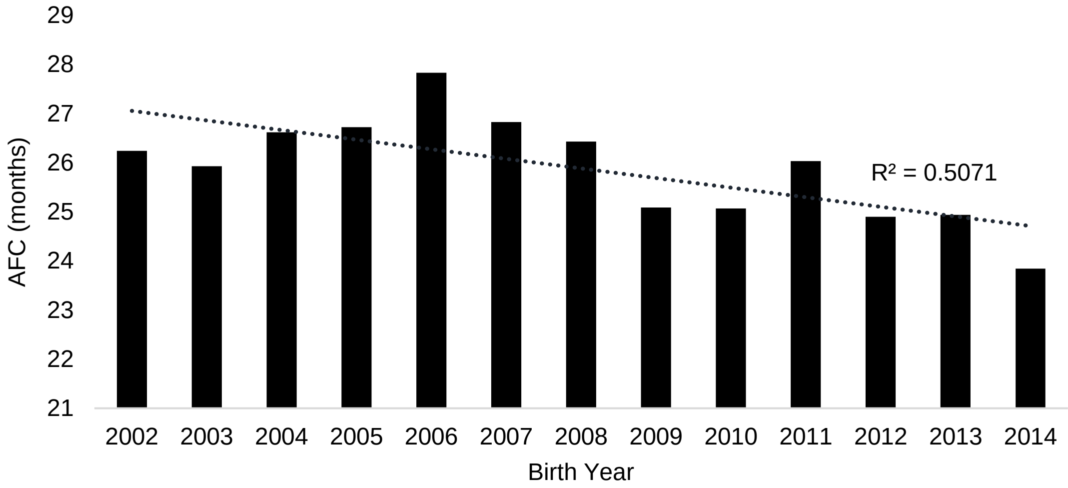

Figure 4 AFC Trend analyses in the TMR herd

In this study, the longevity (days in the system) of a sire's progeny served as an indicator of the sustainability of its genetic contribution to the herd. The corresponding lifetime milk yield as a function of days in the system demonstrates the relationship between time spent on the farm and production efficiency. Our findings from the pasture-based herd reveal a robust linear regression between sires (Figure 5).

For instance, the progeny of the lowest-ranking sire spent a mean of 901 days on the farm, yielding 3 kg of milk per day in the system. Conversely, the progeny of the highest-ranking sire had a mean value of 2040 days in the system, exhibiting a production efficiency of 12 kg/day. The regression coefficient for production efficiency ($R^2 = 0.5792$) shows that there were progeny groups with higher lifetime mean milk yield that did not rank highest on longevity. The mean days on the farm for the sire with the highest-ranking progeny based on milk yield (13kg/day) was 1728 days.

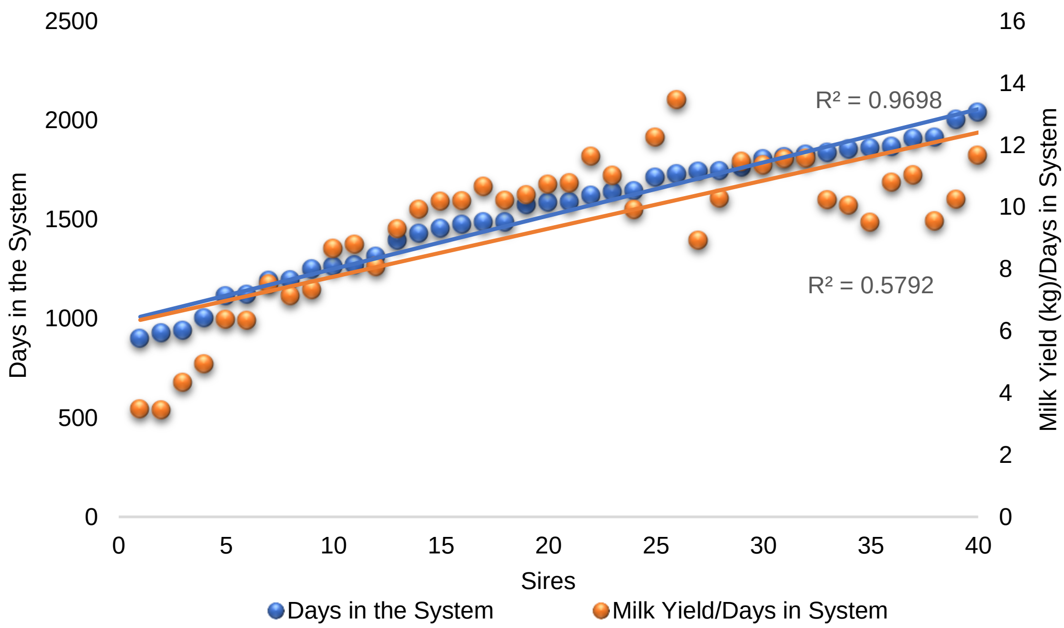

Figure 5 Pasture-based sire progeny performance

The results from the TMR herd depict a similar linear regression in sire ranking based on progeny longevity (Figure 6). In this herd, the progeny of the lowest-ranking sire spent 165 days in the system, yielding 0 kg per day. Conversely, the progeny of the highest-ranking sire spent a mean of 2263 days in the system, exhibiting a production efficiency of 17 kg per day. The correlation between days in the system and lifetime milk yield was more pronounced in this herd, as evidenced by the regression coefficient for milk yield per day in the system ($R^2 = 0.8074$). These findings illuminate the variability in mean progeny longevity and production efficiency within both the pasture-based and TMR herds, enabling producers to concentrate their selection efforts on high-ranking sires. These results, further suggest an inflection point for optimal lifetime efficiency in both herds that can be investigated.

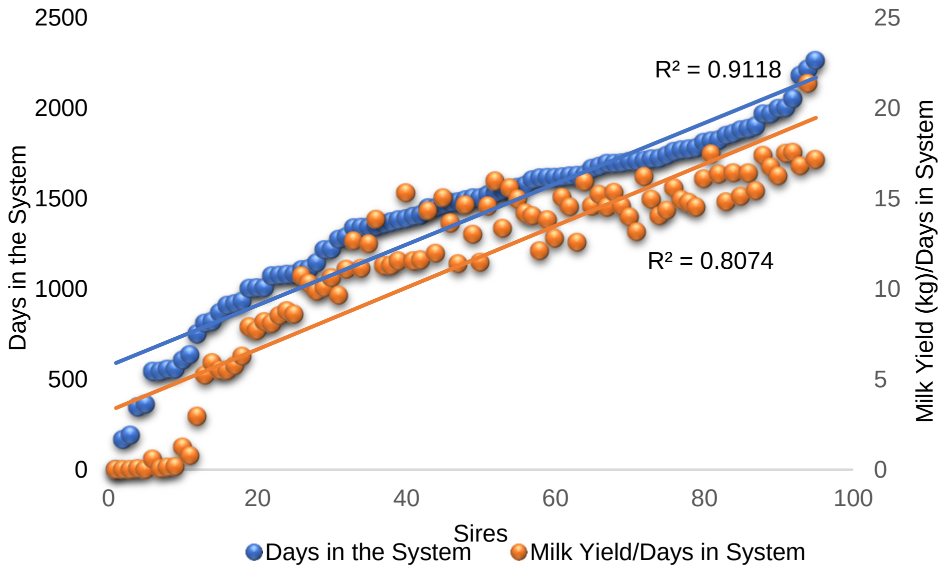

Figure 6 TMR sire progeny performance

In the pasture-based herd, survivability until the first lactation presents a favorable scenario, with merely 7.3% of heifers culled before their initial calving event (Figure 7). However, a notable spike in culling is observed during the first lactation phase, accounting for 29.8% of instances. Informal discussions with the producer corroborate an explicit emphasis on fertility in first-lactation cows, with selection against individuals displaying anoestrous or poor conception. Survivability beyond the third lactation remained limited, with a mere 25% of cows culled following a fourth calving event.

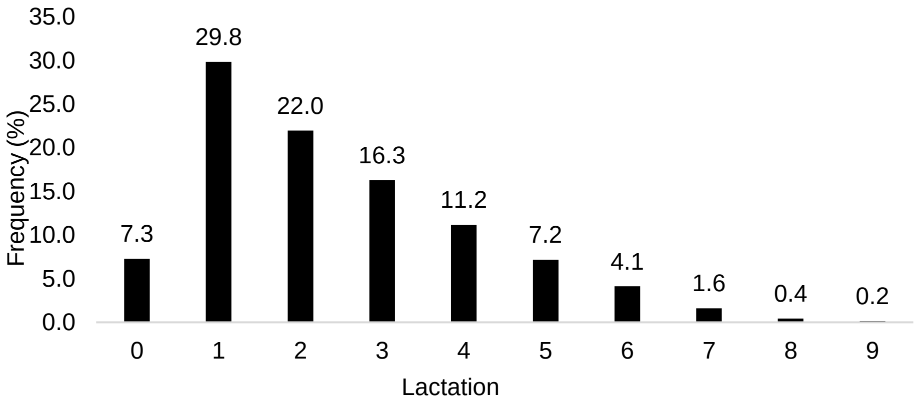

Figure 7 Distribution of exits in the pasture-based herd

Conversely, the survivability records in the TMR herd illustrate a different scenario, indicating a higher likelihood of heifers leaving the herd before their first calving event, with 22.03% culled before their first lactation (Figure 8). Furthermore, the portion of cows who survived beyond a fourth calving event dwindles to 17% in this herd. Personal communication with the producer confirmed that management strategies in this context prioritize a high throughput of replacement heifers and maximal exploitation of milk yield potential. This emphasis leads to challenges in conception and exacerbates udder health issues, ultimately negatively impacting culling rates.

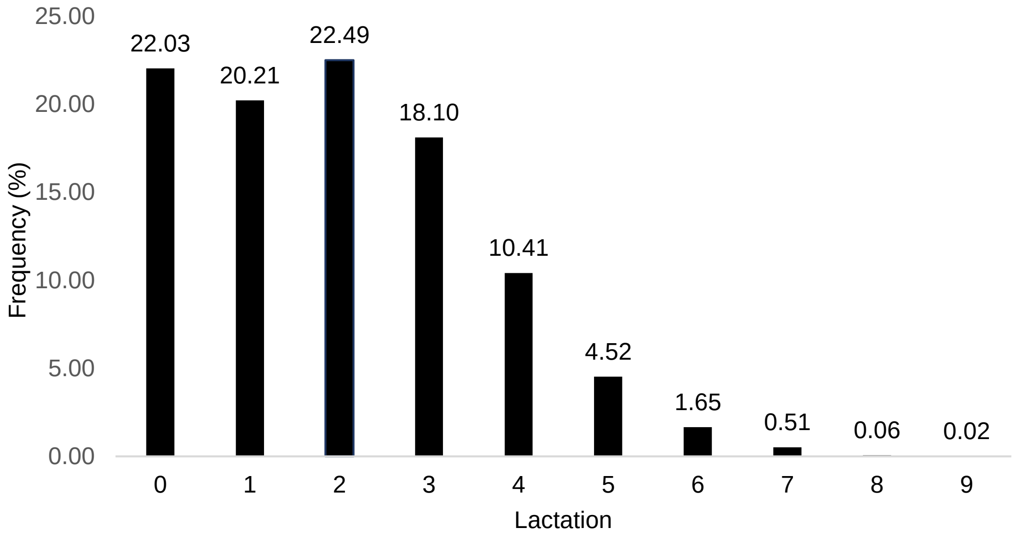

Figure 8 Distribution of exits in the TMR herd

Discussion

The distinguishable AFC distribution patterns observed in the pasture-based and TMR herds emphasize the significant impact of system-specific heifer-rearing practices on overall herd performance metrics. Publications suggest that achieving an AFC close to 24 months remains the benchmark for economic and animal sustainability in both conventional and automated herds (Atashi *et al*., 2021; İlhan *et al*., 2022; Kusaka *et al*., 2022; Vargas-Leitón *et al*., 2023). Variations in achieving the desired 24-month AFC, particularly in the TMR herd, may stem from a voluntarily extended fertility cycle or management challenges hindering optimal heifer growth and reproductive functioning.

The utilization of technology for heifer fertility management begins between 13 and 15 months of age in both herds. Consequently, the pre-pubertal management environment plays a crucial role in shaping the performance of heifers entering the automated monitoring group. Carulla *et al*. (2023) delineate three animal-specific areas for optimizing heifer management: biological functioning and health, cognitive judgment, and expression of natural behavior. Within these realms, particular attention is paid to factors including heifer housing, dietary regimens, colostrum feeding protocols, weaning practices, group dynamics, biosecurity measures, vaccination strategies, and fertility management. The pre-weaning period is a pivotal phase for achieving early developmental milestones, necessitating adequate housing conditions and timely colostrum provision to uphold immunity and biosecurity standards.

The considerations mentioned are non-exhaustive and bear significance across diverse dairy management approaches, encompassing both TMR and pasture-based systems (Verdon, 2021; Machado and Ballou, 2022; Mahendran *et al*., 2022). To investigate the trends in mean AFC as a factor of the year of birth illustrates a downward trend for both herds. Year-on-year evaluation is essential to study management and/or environmental factors contributing to variation over the study period. The trends observed in both herds suggest that automated fertility management played a crucial role in enhancing timed heifer insemination and conception. Research by Das *et al*. (2023) elucidates how automated activity monitoring using Afimilk sensors improved oestrus detection and conception rates, resulting in shorter fertility intervals such as AFC. Similarly, Kliś *et al*. (2021) highlighted the post-partum sensitivity of automated oestrus detection, leading to fewer services to conception and a lower CI.

Pre-pubertal management practices in both herds probably contributed to variations in AFC distribution across different age brackets and between birth years over the study period. Results suggest that automated activity monitoring and data capture software platforms facilitated precise oestrus detection and improved conception rates, ultimately leading to a decreasing trend in AFC. Digital pedigree records in this study demonstrate a capacity for advanced herd genetic evaluation functions and temporal sire selection analyses. The AI sire reports extracted from the Afifarm database highlight the potential of the software as a tool for sire ranking and selection. Meticulous recording of historic sire numbers and corresponding insemination dates in both herds facilitated evaluation alongside historic progeny performance values.

While sire ranking and selection based on progeny performance are established methods, selection models must integrate contemporary progeny-data platforms (Talokar *et al*., 2021). Herd-specific co-variables can influence sire rankings, underscoring the necessity to incorporate on-farm pedigree data and progeny performance for tailored genetic and economic advancement (Lopez-Villalobos *et al*., 2020). Moreover, insemination data could serve as an indicator of inferior semen fertility, potentially impacting delayed conception rates on the farm (Haile-Mariam and Pryce, 2021; Pacheco *et al*., 2021). The value of historic AMS insemination records for South African herds was demonstrated by Kgari *et al*. (2022). In their study, they applied AI records to establish genetic parameters. Their study highlights the declining longevity in South African dairy herds and emphasizes the need to quantify selection norms for improving fertility and welfare traits early in the selection process. Service records from AMSs provide phenotypic data correlating with early-life ranking for heifers at the time of first service, aligning with lifetime fertility performance.

The examination of cull records across both herds reveals a notable trend: the majority of animals fail to survive beyond a third calving event. These findings align with documented survivability metrics for high-producing cows, indicating that most high-yielding individuals do not surpass 4 years of age (De Vries and Marcondes, 2020). Such premature exits stand in contrast to the welfare and longevity objectives advocated for sustainable dairy production (Ventura *et al*., 2021).

A consistent theme across high-yielding herds is the quantification of exit reasons, which often revolve around fertility issues, feet and leg problems, mastitis, and suboptimal milk yield levels (Dallago *et al*., 2021). The exit reasons documented for both the herds in this study confirm this trend, with sub-optimal fertility, mastitis and low milk yield contributing to the majority of exits. Heifers in both herds were primarily culled for low fertility and welfare challenges. The adoption of automated continuous monitoring emerges as a promising approach to proactively manage herds and promote longevity. For instance, Ranzato *et al*. (2022) have developed an algorithm capable of predicting the survivability of first-parity cows past their third calving event based on lactation parameters measured in early and mid-lactation. The demonstrated repeatability of this model across diverse farm settings underscores the potential of automated records to monitor cull risk effectively in various production environments.

The imperative to enhance survivability in dairy herds necessitates a holistic approach that integrates automated records. Schuster *et al*. (2020) underscore the importance of monitoring longevity alongside key farm-specific variables, emphasizing the need for comprehensive assessment encompassing heifer performance, milk yield, health, welfare, and fertility. As economic and sustainability pressures drive a paradigm shift towards prioritizing survivability, producers are tasked with optimizing individual cow longevity while maximizing herd production output (Grzesiak *et al*., 2022). This goal is attainable through the implementation of a decision support team dedicated to conducting routine, thorough evaluations of performance records. By leveraging automated monitoring tools, producers can effectively strike a balance between milk yield and other traits crucial for sustainable fertility and welfare, ensuring the economic viability of future dairy herds.

In summary, the advent of digitalized dairy management heralds a paradigm shift in data acquisition and analytical prowess. The seamless integration of sensor-based hardware components with management software platforms melds the biophysical intricacies of dairy production with digitized analytical outputs (Jiang *et al*., 2023; Kleen and Guatteo, 2023). Advancements in the Internet of Things (IoT) connectivity, cloud processing, and machine learning further expedite the flow of data from sensors to management software interpretation (Akbar *et al*., 2020; Morrone *et al*., 2022; De Vries *et al*., 2023). Real-time alerts and data reports furnish managers with the fodder for informed decision-making, driving efficiency and precision.

Conclusion

Data from the Afifarm herd management software in South African pasture-based and TMR herds offer valuable insights into herd dynamics. This study suggests that historic time-trend herd data analysis can be a tool among animal scientists, veterinarians, and automated dairy data scientists. Future studies should aim to expand the scope by investigating a broader range of records and including more herds for evaluation. By doing so, one can further validate the effectiveness of automated data in monitoring dairy performance and facilitate research on the South African dairy herds.

Authors' Contributions

The original manuscript was drafted by AUG, but a comprehensive revision was done by EVMK and HHM, all authors provided editorial suggestions and approved the final manuscript.

Conflict of Interest Declaration

Authors declare that there was no conflict of interest.

Aknowledgement

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References

Agrawal, S., Ghosh, S., Kaushal, S., Roy, B., Nigwal, A., Lakhani, G.P., Jain, A. & Udde, V., 2023. Precision Dairy Farming: A Boon for Dairy Farm Management. Int. J. Innov. Sci. Res. Technol. 8.

Akbar, M.O., Shahbaz Khan, M.S., Ali, M.J., Hussain, A., Qaiser, G., Pasha, M., Pasha, U., Missen, M.S., Akhtar, N., 2020. IoT for Development of Smart Dairy Farming. J. Food Qual. 2020 (1), 1-8. https://doi.org/10.1155/2020/4242805.

Atashi, H., Asaadi, A. & Hostens, M., 2021. Association between age at first calving and lactation performance, lactation curve, calving interval, calf birth weight, and dystocia in Holstein dairy cows. PLoS ONE. 16, e0244825. https://doi.org/10.1371/journal.pone.0244825.

Bianchi, M.C., Bava, L., Sandrucci, A., Tangorra, F.M., Tamburini, A., Gislon, G. & Zucali, M., 2022. Diffusion of precision livestock farming technologies in dairy cattle farms. Anim. 16, 100650. https://doi.org/10.1016/j.animal.2022.100650.

Carulla, P., Villagrá, A., Estellés, F. & Blanco-Penedo, I., 2023. Welfare implications on management strategies for rearing dairy calves: A systematic review. Part 1-feeding management. Front. Vet. Sci. 10, 1148823. https://doi.org/10.3389/fvets.2023.1148823.

Cogato, A., Brščić, M., Guo, H., Marinello, F. & Pezzuolo, A., 2021. Challenges and Tendencies of Automatic Milking Systems (AMS): A 20-Years Systematic Review of Literature and Patents. Anim. 11, 356. https://doi.org/10.3390/ani11020356.

Dallago, G.M., Wade, K.M., Cue, R.I., McClure, J.T., Lacroix, R., Pellerin, D. & Vasseur, E., 2021. Keeping Dairy Cows for Longer: A Critical Literature Review on Dairy Cow Longevity in High Milk-Producing Countries. Anim. 11, 808. https://doi.org/10.3390/ani11030808.

Das, S., Shaji, A., Nain, D., Singha, S., Karunakaran, M. & Baithalu, R.K., 2023. Precision technologies for the management of reproduction in dairy cows. Trop. Anim. Health Prod. 55, 286. https://doi.org/10.1007/s11250-023-03704-2.

De Vries, A., Bliznyuk, N. & Pinedo, P., 2023. Invited Review: Examples and opportunities for artificial intelligence (AI) in dairy farms. Appl. Anim. Sci. 39, 14–22. https://doi.org/10.15232/aas.2022-02345.

De Vries, A. & Marcondes, M.I., 2020. Review: Overview of factors affecting productive lifespan of dairy cows. Anim. 14, s155-s164. https://doi.org/10.1017/S1751731119003264.

Gargiulo, J.I., Lyons, N.A., Clark, C.E.F. & Garcia, S.C., 2022. The AMS Integrated Management Model: A decision-support system for automatic milking systems. Comput. Electron. Agric. 196, 106904. https://doi.org/10.1016/j.compag.2022.106904.

Gaworski, M., 2021. Implementation of Technical and Technological Progress in Dairy Production. Processes. 9, 2103. https://doi.org/10.3390/pr9122103.

Giordano, J.O., Sitko, E.M., Rial, C., Pérez, M.M. & Granados, G.E., 2022. Symposium review: Use of multiple biological, management, and performance data for the design of targeted reproductive management strategies for dairy cows. J. Dairy Sci. 105, 4669-4678. https://doi.org/10.3168/jds.2021-21476.

Gresse, A.U., 2018. Alternative approaches for analyses of production performance from automatic milking systems in South Africa. MSc Dissertation, University of Pretoria, South Africa http://hdl.handle.net/2263/70581.

Groher, T., Heitkämper, K. & Umstätter, C., 2020. Digital technology adoption in livestock production with a special focus on ruminant farming. Animals. 14, 2404-2413. https://doi.org/10.1017/S1751731120001391.

Grzesiak, W., Adamczyk, K., Zaborski, D. & Wójcik, J., 2022. Estimation of Dairy Cow Survival in the First Three Lactations for Different Culling Reasons Using the Kaplan–Meier Method. Animals. 12, 1942. https://doi.org/10.3390/ani12151942.

Milk SA., 2024. Statistics, LACTO DATA, Vol. 27(1), June 2024, a Milk SA publication compiled by the MPO, Pretoria.

Haile-Mariam, M. & Pryce, J.E., 2021. Use of insemination data for joint evaluation of male and female fertility in predominantly seasonal-calving dairy herds. J. Dairy Sci. 104, 11807-11819. https://doi.org/10.3168/jds.2020-20006.

Henchion, M.M., Regan, Á., Beecher, M. & MackenWalsh, Á., 2022. Developing 'Smart' Dairy Farming Responsive to Farmers and Consumer-Citizens: A Review. Anim. 12, 360. https://doi.org/10.3390/ani12030360.

İlhan, G., Çavuşoğlu, E. & Orman, A., 2022. What is the best first-calving age of cows in robotic milking farms? Ital. J. Anim. Sci. 21, 324-330. https://doi.org/10.1080/1828051X.2022.2031319.

Jiang, B., Tang, W., Cui, L. & Deng, X., 2023. Precision Livestock Farming Research: A Global Scientometric Review. Anim. 13, 2096. https://doi.org/10.3390/ani13132096.

Kgari, R.D., Muller, C., Dzama, K. & Makgahlela, M.L., 2022. Estimation of Genetic Parameters for Heifer and Cow Fertility Traits Derived from On-Farm AI Service Records of South African Holstein Cattle. Anim. 12, 2023. https://doi.org/10.3390/ani12162023.

Kleen, J.L. & Guatteo, R., 2023. Precision Livestock Farming: What Does It Contain and What Are the Perspectives? Animals. 13, 779. https://doi.org/10.3390/ani13050779.

Kliś, P., Sawa, A., Piwczyński, D., Sitkowska, B. & Bogucki, M., 2021. Prediction of cow's fertility based on data recorded by automatic milking system during the periparturient period. Reprod. Domest. Animals. 56, 1227-1234. https://doi.org/10.1111/rda.13981.

Kusaka, H., Yamazaki, T. & Sakaguchi, M., 2023. Association of age at first calving with longevity, milk yield, and fertility up to the third lactation in a herd of Holstein dairy cows in Japan. J. Reprod. Dev. 69, 291-297. https://doi.org/10.1262/jrd.2023-012.

Kusaka, H., Yamazaki, T. & Sakaguchi, M., 2022. Association of the age and bodyweight at first calving with the reproductive and productive performance in one herd of Holstein dairy heifers in Japan. Vet. Rec. Open 9, e44. https://doi.org/10.1002/vro2.44.

Lopez-Villalobos, N., Wiles, P.G. & Garrick, D.J., 2020. Sire selection and genetic improvement of dairy cattle assuming pure market competition. J. Dairy Sci. 103, 4532-4544. https://doi.org/10.3168/jds.2019-17582.

Machado, V.S. & Ballou, M.A., 2022. Overview of common practices in calf raising facilities. Transl. Anim. Sci. 6, txab234. https://doi.org/10.1093/tas/txab234.

Mahendran, S.A., Wathes, D.C., Booth, R.E. & Blackie, N., 2022. A survey of calf management practices and farmer perceptions of calf housing in UK dairy herds. J. Dairy. Sci. 105, 409-423. https://doi.org/10.3168/jds.2021-20638.

Markov, N., Stoycheva, S., Hristov, M., Mondeshka, L., Atanasova, T., Blagoev, I., Petrov, P., Valova, I., Valov, N. & Mladenova, T., 2022. Smart Dairy Farm - Digitalization and Innovation, in: 2022 8th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE). Presented at the 2022 8th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE), IEEE, Ruse, Bulgaria, pp. 1-4. https://doi.org/10.1109/EEAE53789.2022.9831220.

Meissner, H.H., Blignaut, J.N., Smith, H.J., & Du Toit, C.J.L. (2023). The broad-based eco-economic impact of beef and dairy production: A global review. S. Afr. J. Anim. Sci., 53(2), 250-275.

Morrone, S., Dimauro, C., Gambella, F. & Cappai, M.G., 2022. Industry 4.0 and Precision Livestock Farming (PLF): An up to Date Overview across Animal Productions. Sensors. 22, 4319. https://doi.org/10.3390/s22124319.

Ozella, L., Brotto Rebuli, K., Forte, C. & Giacobini, M., 2023. A Literature Review of Modeling Approaches Applied to Data Collected in Automatic Milking Systems. Animals. 13, 1916. https://doi.org/10.3390/ani13121916.

Pacheco, H.A., Battagin, M., Rossoni, A., Cecchinato, A. & Peñagaricano, F., 2021. Evaluation of bull fertility in Italian Brown Swiss dairy cattle using cow field data. J. Dairy. Sci. 104, 10896-10904. https://doi.org/10.3168/jds.2021-20332.

Piwczyński, D., Brzozowski, M. & Sitkowska, B., 2020. The impact of the installation of an automatic milking system on female fertility traits in Holstein-Friesian cows. Livest. Sci. 240, 104140. https://doi.org/10.1016/j.livsci.2020.104140

Ranzato, G., Adriaens, I., Lora, I., Aernouts, B., Statham, J., Azzolina, D., Meuwissen, D., Prosepe, I., Zidi, A. & Cozzi, G., 2022. Joint Models to Predict Dairy Cow Survival from Sensor Data Recorded during the First Lactation. Animals. 12, 3494. https://doi.org/10.3390/ani12243494.

Schuster, J.C., Barkema, H.W., De Vries, A., Kelton, D.F. & Orsel, K., 2020. Invited review: Academic and applied approach to evaluating longevity in dairy cows. J. Dairy. Sci. 103, 11008-11024. https://doi.org/10.3168/jds.2020-19043.

Shalloo, L., Byrne, T., Leso, L., Ruelle, E., Starsmore, K., Geoghegan, A., Werner, J. & O'Leary, N., 2021. A review of precision technologies in pasture-based dairying systems. Ir. J. Agric. Food Res. 59. https://doi.org/10.15212/ijafr-2020-0119.

Simitzis, P., Tzanidakis, C., Tzamaloukas, O. & Sossidou, E., 2021. Contribution of Precision Livestock Farming Systems to the Improvement of Welfare Status and Productivity of Dairy Animals. Dairy. 3, 12-28. https://doi.org/10.3390/dairy3010002.

Singh, A.K., Bhakat, C., Ghosh, M.K. & Dutta, T.K., 2021. Technologies used at advanced dairy farms for optimizing the performance of dairy animals: A review. Span. J. Agric. Res. 19, e05R01. https://doi.org/10.5424/sjar/2021194-17801.

Snedecor, G.W. & Cochran, W.G., 1980. Statistical methods (7th Ed.). Iowa State University Press, 234.

Talokar, A.J., Kumar, H., Mehrotra, A., Kaisa, K., Saravanan, K.A., Panigrahi, M., Dutt, T., Bhushan, B., 2021. Recent Advances in Sire Evaluation Methods: A Review. IJAR. https://doi.org/10.18805/IJAR.B-4280.

Tippenhauer, C.M., Plenio, J.-L., Madureira, A.M.L., Cerri, R.L.A., Heuwieser, W. & Borchardt, S., 2021. Factors associated with estrous expression and subsequent fertility in lactating dairy cows using automated activity monitoring. J. Dairy. Sci. 104, 6267-6282. https://doi.org/10.3168/jds.2020-19578.

Vargas-Leitón, B., Romero-Zúñiga, J. J., Castillo-Badilla, G. & Saborío-Montero, A. (2023). Optimal age at first calving in pasture-based dairy systems. Dairy. 4, 581-593.

Ventura, G., Lorenzi, V., Mazza, F., Clemente, G.A., Iacomino, C., Bertocchi, L. & Fusi, F., 2021. Best Farming Practices for the Welfare of Dairy Cows, Heifers and Calves. Animals. 11, 2645. https://doi.org/10.3390/ani11092645.

Verdon, M., 2021. A review of factors affecting the welfare of dairy calves in pasture-based production systems. Anim. Prod. Sci. 62, 1-20. https://doi.org/10.1071/AN21139.

Yang, W., Edwards, J.P., Eastwood, C.R., Dela Rue, B.T. & Renwick, A., 2021. Analysis of adoption trends of in-parlor technologies over a 10-year period for labor saving and data capture on pasture-based dairy farms. J. Dairy. Sci. 104, 431-442. https://doi.org/10.3168/jds.2020-18726.