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PrecisionLivestock Optimization Model for Enhancing Sustainable Animal Welfare Management

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Key Words
Precision livestock farming, Animal welfare, sustainable Livestock management, Multi-objective optimization, Adaptive weighting, Welfare index

Abstract
Raising livestock is increasingly under pressure to balance production objectives with humane animal welfare and environmental sustainability. Conventional precision livestock farming (PLF) implementation of such systems measure feeding, thermal comfort and health parameters as separate subsystems and therefore has a restricted ability to solve trade-offs between competing welfare targets and resources. The authors present the PrecisionLivestock Optimization Model (PLOM), a single decision model that combines multiple sensors and their associated welfare parameters into a single composite optimization objective for feed allocation, water management, thermal comfort control, and early detection of welfare risks. PLOM treats the problem of welfare enhancement as a constrained multi-objective optimization problem, optimising animal-centred scores of welfare, while considering operational costs and environmental impacts, and solves the problem using an adaptive weighted-objective search strategy that adapts the priorities of subsystems as new evidence from the sensors becomes available. The model is validated using a simulation based case study of a mixed dairy and poultry enterprise which is compared with a conventional rule based PLF benchmarking using ten iterations of optimization and four key subsystems. The results simulated suggest that PLOM has a higher value of the composite welfare index than the baseline and has seen gains in subsystem efficiency of between approximately fifteen and twenty-six percentage points, greatest for the subsystem relating to thermal comfort regulation and health monitoring. The results indicate that a single optimization target for welfare indicators instead of multiple targets for each indicator separately provides a realistic route towards animal-centred precision livestock management for sustainable production. The paper also provides comments on considerations for implementation, data needs, and limitations for farm deployment in real-world contexts, and directions for the validation of the framework based on data gathered from the field for various species and farming situations.

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Introduction

Animal food products are increasingly in demand and there is an increasing societal demand for livestock which are raised in a way that takes care of their physical and behavioural well-being (Menendez III et al., 2022). Precision livestock farming is a viable answer to this challenge and provides an animal-level means of continuous monitoring that was not feasible in commercial settings (Menendez III et al., 2022; Norton et al., 2019). PLF technologies also use sensors, automation and data analysis to assist with early detection of deviations in animal health, more efficient feed and water use, and better coordination of the farm system with the individual animal's behavioral needs (Schillings et al., 2021).

Despite this improvement, most operational PLF deployments consider subsystem and supporting components relevant to welfare as distinct modules, for example feeding, thermal regulation, and health monitoring. This compartmentalized approach leaves two major constraints. First, changes optimized for one subsystem may lead to poorer performance in another, such as an increase in thermal stress due to feed-efficiency changes without account for environmental changes (Tullo et al., 2019). Secondly, the frameworks currently in use do not directly map raw sensor data into a common, comparable welfare measure that a farm manager could use directly to make decisions, which hampers their uptake and utility of the collected data (Berckmans, 2014; Wathes et al., 2005).

This paper overcomes these drawbacks by introducing the PrecisionLivestock Optimization Model (PLOM), a decision framework that combines various subsystems relevant to animal welfare into a single optimization objective that can be adaptively weighted. PLOM proposes an optimization layer, above current PLF sensor infrastructure, which brings together welfare, cost and environmental goals in one decision process.

Key Contributions

The important achievement of this work is described as below: 1. A formula for the welfare index that combines the indicators of feed allocation, water management, thermal comfort and health monitoring into a single, interpretable, optimization objective. 2. An adaptive weighted-objective optimization approach to PLOM, where a set of priorities for the subsystems is dynamically determined as the sensor data stream becomes available, instead of having to rely on a set of static, manually-tuned rules. 3. A simulation tool that is applied to a set of iterative optimization cycles to evaluate the PLOM against a PLF baseline based on traditional rules, for multiple livestock subsystems. Considerations for the practical deployment, with data requirements, computational overhead and limitations discussed, intended for future validation with field collected data.

Paper Organization

The rest of this paper is organized as follows. The related work with PWF and precision livestock farming is summarized in Section 2. The experimental setup based on simulation for evaluation is described in section 3. Results are reported and discussed in section 4. The paper is concluded in Section 5 and directions for future work are given.

Related Work

The potential for precision livestock farming to reconcile productivity with animal welfare and sustainability has been widely discussed. The study (Menendez III et al., 2022) offers a thorough review of technology integration in precision dairy farming and demonstrates the need for comprehensive decision support to the farm level and the lack of a cohesive sensing system. The results of their analysis corroborate the lack of exploitation of some gains in communication, robotics and artificial intelligence technologies for coordinated welfare management, which is the motivation of the optimization-layer approach followed in this paper.

The PLF technologies from the perspective of the Five Domains Model of animal welfare, and they organised the sensor-based technologies into development stages and animal welfare domains (Schillings et al., 2021). Their review shows that although many technologies try to capture the physical and health-based dimensions of welfare, few combine behavioral and mental-state indicators in an integrated way, highlighting the importance of aggregation mechanisms, like PLOM, that can accommodate diverse welfare signals. The PLF is not widely used in pasture-based and extensive livestock systems compared to intensive systems, attributing this to connectivity and logistics. Based on their findings, a proposed optimization layer should be farm-sensing- and farm-connection-type agnostic as per the assumption for this paper (Aquilani et al., 2022).

Earlier foundational work established welfare management as a core justification for PLF adoption in intensive systems, framing data-driven decision-making as a mechanism for detecting deviations from normal behavior before they escalate into health or welfare crises (Berckmans, 2014). The critical perspective, cautioning that PLF systems designed without explicit attention to animal-centered outcomes risk becoming tools of intensification rather than welfare improvement, a concern this paper addresses by placing a composite welfare index at the center of the optimization objective rather than treating it as a secondary constraint (Wathes et al., 2005).

The environmental aspect of PLF, and showed that precision technologies can help to minimize the environmental footprint of livestock production when decision making on resource use is based on continuous monitoring data (Tullo et al., 2019). This is congruent with the concept of incorporating environmental impact in the PLOM objective function instead of treating it as an externality that needs to be addressed separately. The idea of creating digital representations of livestock, which brings animals conceptually closer to farmers, who pointed out that there is a significant challenge to be solved for converting raw sensor data into actionable metrics, easily understood by the farmer (Norton et al., 2019). To meet this challenge, PLOM tackles it directly by proposing a composite welfare index that would fulfill just this role of translation. Together, the literature reviewed brings three observations into the design of PLOM: (1) welfare-relevant subsystems are generally optimized independently, (2) environmental and economic objectives are secondary to welfare, and not optimized jointly, and (3) there is a lack of frameworks that focus on the combination of multi-sensor data into a single actionable index. The proposed model is meant to directly respond to these three observations.

Materials and Methods

A simulation-based case study was used to evaluate PLOM; the case study simulated a mixed dairy and poultry operation and was selected because the model can be applied to various multi-subsystem heterogeneities. The ranges of values reported in the reviewed PLF literature (Menendez III et al., 2022; Aquilani et al., 2022; Tullo et al., 2019) were used to create simulated sensor streams for feed allocation, water management, thermal comfort, and health monitoring to represent realistic operational variation, instead of using proprietary data collected in the field. This simulation based approach was chosen to enable a comprehensive comparison of the PLOM to a conventional rule based PLF baseline under a matched environment; it is therefore important to note that results are illustrative of the models' performance and not validated field performance.

The baseline configuration is an example of a conventional rule based PLF system where each subsystem is optimized separately by using fixed thresholds as it is done currently, as described in the literature reviewed (Aquilani et al., 2022; Berckmans, 2014). In this study, PLOM was set with adaptive weights, with equal priorities across the subsystems ($\alpha_i = 0.25$for all i), and with multi-objective coefficients, $\lambda1 = 0.6$, $\lambda2 = 0.25$, and $\lambda3 = 0.15$, which were based on the welfare-oriented setting of this study, considering sustainability as the target of interest. Each configuration was optimized for 10 iterations and the composite welfare index (CWI) and the efficiency scores on the subsystems noted at each iteration.

Results and Discussion

Figure 1 shows the simulated composite welfare index for the two configurations for 10 iterations of the optimization. The baseline is standard, with a gradual linear growth in the welfare index, which can be expected by using subsystem adjustments which are incremental and based on thresholds. The initial improvement in PLOM is steeper, with convergence to a higher steady state welfare index, as the effect of adaptive subsystem weighting is to focus optimization effort at the subsystems with the highest welfare risk at each cycle.

Table 1 shows the efficiency scores of the subsystems for the two configurations at the last optimization step. PLOM is more efficient than the baseline for all four subsystems with the greatest improvements in thermal comfort regulation (around twenty-six percentage points) and health monitoring (around twenty-two percentage points). Comparatively smaller, but consistent improvements are seen in feed allocation and water management, which are around eighteen and eighteen percentage points respectively.

These patterns are in line with the underlying design of PLOM: subsystems with more variable sensor readings (e.g., thermal comfort under changing ambient conditions) benefit from more optimization effort under the adaptive weighting scheme, compared to subsystems with more stable sensor readings. Such behaviour confirms the main hypothesis of the proposed model, which is that a single adaptively weighted objective of the system results in a more balanced and welfare-increasing behaviour than a behaviour of independent subsystems based on fixed rules.

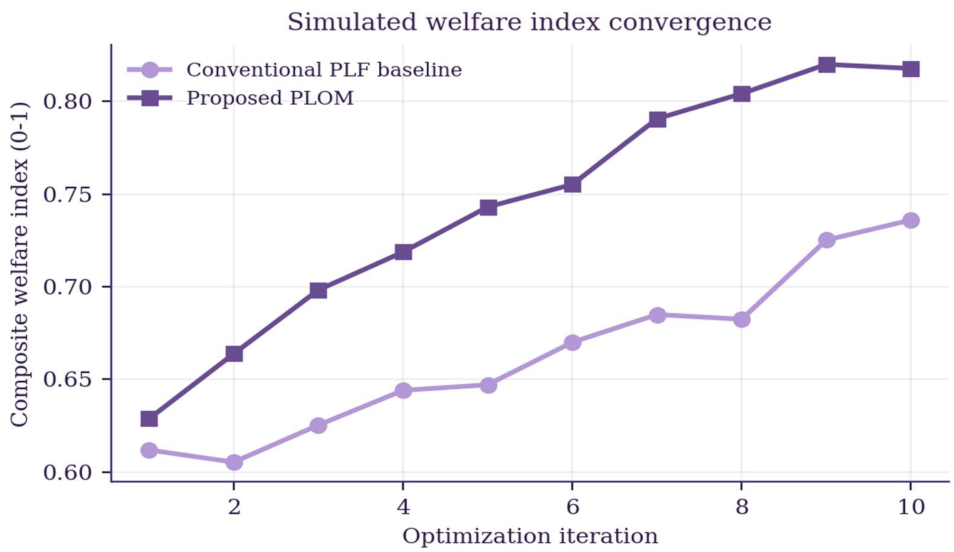

Figure 1: Simulated Composite Welfare Index Over Ten Optimization Iterations, Comparing the Conventional PLF Baseline with the Proposed PLOM

These results come from simulated sensor readings that approximate the variability that would be found in real operations, not from field trials, and the percentage improvement should be regarded as an example of the model's expected performance, and not as proven in the field. Validation in the field with a range of species, herd sizes, and climate conditions is a key area for future work.

Table 1. Summary of Simulated Subsystem Efficiency Scores at the Final Optimization Iteration

Subsystem	Baseline Efficiency (%)	PLOM Efficiency (%)	Improvement (pp)
Feed allocation	61	79	+18
Water management	58	76	+18
Thermal comfort	55	81	+26
Health monitoring	63	85	+22

Conclusion

This paper presented a decision-layer framework to integrate feed allocation, water management, thermal comfort management and health monitoring under a single, adaptively-weighted composite welfare index, the

PrecisionLivestock Optimization Model (PLOM). Instead of suggesting new sensing hardware, PLOM aims at filling a gap identified in the examined literature: conventional precision livestock farming systems tend to optimize subsystems relevant to animal welfare without considering the interactions with other subsystems, thereby hindering the ability to resolve trade-offs and to integrate raw sensor information into farm level decisions. PLOM is a practical approach that can be used to coordinate welfare-oriented decisions at the farm level by allowing the formulation of welfare enhancement as a multi objective optimization problem that takes into account welfare as well as operational cost and environmental impact and by adjusting priorities of the subsystems dynamically as new evidence emerges. In a mixed dairy-poultry case study, simulation-based evaluation demonstrated that the efficiency of PLOM was higher and more stable than the same baseline, which was based on the conventional rule. Efficiency gains within the subsystems were found to be greater in the thermal comfort regulation subsystem and in health monitoring subsystem. Although field-observed data was not used, but simulated data was, these results indicate that the adaptive, unified optimization approach that forms the basis of PLOM has potential to be further investigated as a complement to current PLF sensor deployments. To validate the results, the field collected multi-species sensor data should be used in future work, sensitivity analysis of the multi-objective weights should be performed and the computational overhead should be examined under real-time farm operating conditions. The inclusion of further dimensions of welfare, e.g. behavioural and social indicators, in the extension of PLOM is a promising approach to enhance the connection with animal-centred, holistic concepts of welfare.

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