Modeling and Simulation for Decision Support in Precision Livestock Farming

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MODELING AND SIMULATION FOR DECISION SUPPORT IN PRECISION LIVESTOCK FARMING

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ABSTRACT

Precision Livestock Farming (PLF) is a system that allows real-time monitoring of animals, which comes with many benefits and ensures maximum use of farm resources, thus controlling the health status of animals. Decision support systems in livestock sector help farmers to take actions in support of animal health and better product yield. Due to the complexity of decision making processes, modeling and simulation tools are being extensively used to support farmers and decision makers in livestock industries. Modeling and simulation approaches minimize the risk of making wrong decisions and helps to assess the impact of different strategies before applying them in reality. In this paper, we highlight the role of modeling and simulation in enhancing decision-making processes in precision livestock farming, and provide a comprehensive overview and categorization with respect to the relevant goals and simulation paradigms. We, further, discuss the associated optimization approaches and data collection challenges.

1 INTRODUCTION

As population and incomes increase, there will also be a growth in demand for greater food variety. Studies on human nutrition have shown that worldwide a nutrition transition is taking place, in which people shift towards more affluent food consumption patterns (Bruinsma 2003; Grigg 1995; Popkin 2002). This change of demand patterns from food of plant origin to livestock products such as meat, eggs and milk, together with sizeable population growth, needs to be addressed in a sustainable manner without causing irreparable environmental damage or exceeding global resources.

Precision Livestock Farming (PLF) is one of the most powerful developments amongst livestock farming industry, offering real-time monitoring and management tools for farmers. Modelling and Simulation (M&S) approaches help decision makers and farmers in their decisional problems by providing insights into their managerial practices. Indeed, M&S formalize the real world into a computer-based environment and then imitate the processes and the operations of the real world. Traditionally, simulation modeling converts expert knowledge into dynamic models and simulates them to understand more about
systems. Most recent M&S approaches utilize observational datasets or real-time data to extract models, as well as the parameters needed to perform the simulation.

The contribution of the paper is to provide an overview and categorize the existing simulation and modeling studies on PLF according to different simulation paradigms and the goals they aim for. There are three main M&S paradigms: discrete-event simulation, continuous simulation (also known as system dynamics) and agent-based simulation; and we consider two major goals in Livestock Farming: improving animal welfare/production and reducing GHG emission. Aside from simulation modeling, we also discuss other simpler decision support tools in PLF that use calculators to analyze data.

The paper is structured as follows. We begin by providing a background on Precision Livestock Farming, as enabler for the sophisticated decision support approaches, in Section 2. In Section 3, we provide overview of the different types of decision support that can be of interest in livestock farming. We review the existing modeling, simulation, and data analytics approaches in Section 4. In Section 5, we discuss the challenges related to the data collection for the M&S. Finally, in Section 6 we conclude the paper.

2 PRECISION LIVESTOCK FARMING

Increased demand for animal products has led to increase in the sizes of farms. Managing large number of livestock, ensuring that production demands are met and environmental concerns are not discounted are factors that have caused a shift from traditional to technology-driven farming. Technology can be used to measure the behavior and welfare of the animals. PLF encompasses various aspects of continuous livestock monitoring, such as collection and analysis of data and reporting of certain notable events. The condition (physical and mental) of the animal is continuously changing due to external stimuli. These changes are continuously recorded, stored and transmitted using sensors that measure biosignals. Typical sensors used in PLF include accelerometer, gyroscope, temperature sensors and biosensors. The type of data collected by these sensors include animal gait, speed, position, temperature, sounds, heart rate etc. In addition to the sensors, modelling, simulation and decision support using machine learning learning models are also being successfully used in PLF.

The benefits reaped by adopting PLF in the livestock industry has been tremendous (Hostiou et al. 2017). They include increase in productivity, real-time supply chain management, better marketing and reduction in GHG. Examples of successful PLF projects include: BrightAnimal (Lehr 2011), BioBusiness (Romanini et al. 2011) and (EU-PLF 2016).

PLF consists of the following components: Continuous or real-time processing of sensor data; integration and storage of data; data analysis, simulation and modelling; event detection and signaling. These components help farmers in their decision-making process by enhancing both the management of their daily tasks and the supervision of their herd.

3 DECISION SUPPORT IN PRECISION LIVESTOCK FARMING

The need for decision support is vital in PLF due to its inherent challenges like large heterogeneous data, monitoring of complex systems involving animals and the need for fulfilling multiple goals. There are certain stakeholders, i.e. decision makers, who benefit from the use of decision support in making crucial decisions regarding the management of livestock. Benefits of such a system are manifested in the form of attainment of two ultimate goals: (a) improving animal welfare and (b) GHG reduction. Improving animal welfare is closely related to the livestock production (meat, milk, eggs, etc.), because for a fixed farm size, products from healthy animals surpass those of less healthy ones, both in quality and quantity. Aside from the fact that this affects the farmers income, optimizing animal welfare also reduces the emissions intensity of producing livestock products (i.e. emissions per unit of product) (Herrero 2016). Thus, we need to ensure that the costs of reducing emissions are balanced with the benefits of livestock welfare and production.

Animal welfare: Detection and prevention of animal health issues, and compliance with medical regulations are some of the factors that are considered while aiming towards improved production or yield. Research into animal welfare generally falls into the categories of modelling and simulation-based
optimization methods. In the modelling-based methods, risk assessment, welfare assessment, Machine Learning (ML) and/or statistics based methods are commonly found. Some of the research that has been done in modelling-based methods for animal welfare include measurement of feed intakes (Aydin, Bahr, and Berckmans 2015), identification and classification of chewing patterns in calves (Pegorini et al. 2015), estimation of cattle weight trajectories (Alonso, Villa, and Bahamonde 2015), anomalous activity identification (Vázquez-Diosdado et al. 2019; Adrion et al. 2018) and animal behavioral classification (Dutta et al. 2015). In the simulation-based optimization category, simulation methods are combined with optimization to achieve goals in animal welfare. Discussion about the research in this category is provided in Section 4.5.

**GHG emissions:** Improving production is often done in combination with other factors such as reducing energy consumption, profit maximization and reducing GHG emissions. Compliance with environmental regulations and optimized energy usage are some of the factors in reducing GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) proposed three tiers for classifying the various approaches for combating climate change due to GHG emissions (Yan et al. 2009). Tier 1 consists of simple methods that have various underlying assumptions and are, hence, subject to high uncertainties, while Tier 2 methods have more region/country specific data and are less prone to uncertainties. Tier 3 consists of methods that are detailed and data-driven and have, hence, even lower degree of uncertainties. Among the decision support models proposed in the past, there are models that are simple and conform to IPCC Tiers 1 and 2, and there are simulation based models that conform to IPCC Tier 3 and are more complex.

Table 1 lists some of the decision support models which are based on Tier 1 and Tier 2 methodologies for estimating GHG emissions from livestock.

<table>
<thead>
<tr>
<th>Model</th>
<th>Farm Type</th>
<th>Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>AgRE Calc</td>
<td>Cattle</td>
<td>(SRUC 2014)</td>
</tr>
<tr>
<td>COMET-Farm</td>
<td>Cattle</td>
<td>(Paustian et al. 2017)</td>
</tr>
<tr>
<td>Cool Farm Tool</td>
<td>Cattle</td>
<td>(Hillier 2012)</td>
</tr>
<tr>
<td>Carbon Navigator</td>
<td>Cattle</td>
<td>(Murphy et al. 2013)</td>
</tr>
<tr>
<td>ValorE</td>
<td>Cattle, Pigs</td>
<td>(Acuitis et al. 2014)</td>
</tr>
<tr>
<td>IPCC inventory software</td>
<td>Not limited</td>
<td>(Developed by SPIRIT 2020)</td>
</tr>
<tr>
<td>ALU software</td>
<td>Not limited</td>
<td>(‘ALU software’ 2010)</td>
</tr>
</tbody>
</table>

In summary, there have been many different kinds of studies into improving animal welfare, production yield and reducing GHG emissions of livestock farms. Incorporating ML and deep learning algorithms in decision support for PLF helps achieve several goals.

## 4 M&S FOR DECISION SUPPORT IN LIVESTOCK FARMING

Decision management is becoming increasingly important in today’s livestock farming, and decision support systems (DSS) play a vital role in management and making the right decision at the right moment. DSS integrate optimization, modeling and simulation in a computer-based environment, in order to provide the required level of insight in the decisional problem. An important step in the development of effective real-world DSS is to formalize the decisional problem into a model (modelling phase) and then to simulate possible scenarios in order to evaluate their performance, to screen alternatives and finally focus only on the promising ones. Therefore, simulation refers to imitating the operations and processes of a system in the real world; while modeling is the process of understanding and describing the behavior of a system (Banks et al. 2010).

To assist farm managers in their decision processes, M&S delivers valuable insights on the potential impact of various decisions they make before actually implementing them in the real-world. Most of the studies concerning M&S approaches in PLF, are process-oriented simulation methods. On a farm, various objects or subroutines represent processes. Some examples of major processes in a farm are: feed...
availability, the herd, manure handling, and gas emissions. In this section we first describe different M&S paradigms, and we describe the use of the processes in M&S more in detail. Then we categorize the studies devoted to M&S in PLF regarding M&S paradigms.

4.1 Traditional M&S Paradigms

Simulation modeling is a process that generally involves converting expert knowledge into dynamic models and simulating them to understand more about the system. This traditional simulation modeling has the advantage that a modeler can use existing knowledge to create meaningful simulation models representing the system. These handcrafted models are also useful for testing theories about how a system works. If a model faithfully represents a system, then it will produce the same behavior as the real system. In this scenario the model can be thought of as a hypothesis for how the real system works. The most popular simulation paradigms are: discrete-event simulation, continuous simulation (also known as system dynamics) and agent-based simulation, which we elaborate in the following.

4.1.1 Discrete-Event Simulation

A discrete-event simulation (DES) models the operation of a system as a (discrete) sequence of events in time. Each event occurs at a particular instant in time and marks a change of state in the system (Robinson 2004). Traditionally, DES models are based on data extracted from a physically existing system or a system that has been developed and tested before (i.e. historical data). This data can be enhanced with a set of experimental rules and mathematical algorithms to enable prediction of system behaviors well in advance.

To improve animal welfare, modeling the spread of disease in a large farm can help to simulate the disease behavior and make the best decision to prevent it from spreading more. Considering finite number of infectious stages (i.e. Susceptible, Intermittent and Persistent), transiting from one stage to another with a given rate, is an event which makes changes to the herd system (Sørensen et al. 2017; Bruijn, Hogeveen, and Stassen 2010). Considering GHG emissions, DES approaches can again be used to simulate diseases and production of an animal over time. Life Cycle Assessment (LCA) methods can then be applied to quantify the GHG impact of the disease (Mostert et al. 2018).

4.1.2 Continuous Simulation

Continuous simulation (CS), also known as System Dynamics, is a methodology to recognize and solve the system problems by analyzing the information feedback, dealing with the dynamic structure and feedback mechanism between the qualitative and quantitative factors of the complex system, to obtain the overall cognition and problem solving of the system (Sterman 2000). In the CS methodology, a problem or a system (e.g., ecosystem, farming system or mechanical system) may be represented as a causal loop diagram (Sterman 2000). Causal loop diagrams aid in visualizing a system’s structure and behavior, and analyzing the system qualitatively. To perform a more detailed quantitative analysis, a causal loop diagram is transformed to a stock and flow diagram. A stock is the term for any entity that accumulates or depletes over time (i.e. milk production, feed intake, manure production or GHG emission). A flow is the rate of change in a stock, in terms of formulas or equations with stocks as the variables in the formula. Depending on the problem at hand, modeling the equations can be done in continuous or discrete time.

In (Rotz, Montes, and Hafner 2011) the major components or processes of the model include available feeds, animal intake and manure production, and manure handling. The feeds available and their nutrient contents are provided through user input. Balanced rations are prepared for each animal group on the farm and their feed intake is determined to meet their energy and protein requirements. Based upon feed intake, growth and milk production, the nutrient output in manure is predicted. From this nutrient excretion, emissions are predicted as a function of weather conditions and management practices.
Regarding animal welfare, stocks in CS can be defined as bacteria concentration which are transported via surface water or air (Widgren et al. 2019). Other studies of use of CS in modelling the dynamics of GHG emissions or animal welfare can be found in Table 2.

### 4.1.3 Agent-Based Modeling

Agent-based modeling (ABM) is commonly used to study the dynamic movement behaviors of various types of systems, such as flocks of birds, pools of fish, pedestrian crowds, road traffic and livestock. A system can be simulated using a mobile agent-based model if it contains many similar agents, such as people who move around in a shared environment, act autonomously, and only have local knowledge (and possibly global knowledge about the environment: like a familiar building’s layout).

On a dairy herd, agents can be defined as individual cows. Al-Mamun and Grohn (2017) developed a multiscale agent based simulation model of a dairy herd. In their model each cow was tracked from birth to death, residing at different management operations; adult/milking, calf and heifer. Their model was successfully applied to estimate critical parameters (i.e. insemination time) for management decisions.

### 4.2 Data-Driven M&S

Data-Driven Simulation (DDS) is an approach where the simulation models are parameterized by data, allowing users to create and run a simulation model without the need to do explicit modelling. The goal of DDS is to generate simulation models directly from external data sources using data structuring and analysis algorithms for creating and configuring the model. The degree of parameterization within data-driven simulation in research varies, affecting the flexibility of scenarios which can be modelled. Some DDS approaches use data only to estimate the model parameters (Al-Mamun et al. 2018), but other studies also drive the model structure from observational data (Widgren et al. 2019).

Dynamic Data-Driven Simulation (DDDS) is a type of data-driven simulation which uses real-time data to detect the system model and feeds the simulation results back into the model continuously to gain more accurate and on time results.

### 4.3 Simulation Approaches vs Goals

M&S approaches in livestock are applied to either improve animal welfare or reduce GHG emissions. IPCC-based M&S approaches are mostly process-based, which were primarily developed by scientists to better understand the processes involved and to predict how they interact. Some CS models in PLF, consider manure management processes in their modules (Holzworth et al. 2014), some have processes for enteric fermentation (Bannink et al. 2010), and some have more (Schils et al. 2007), which is the main difference between CS approaches. The addition of new processes to an existing model structure, requires much time and effort to develop or to adapt, and that is a weakness compared to the simpler and more flexible DS models of Table 1. Table 2 illustrates M&S studies on livestock according to three simulation paradigms: DES, CS and ABM; and the most relevant PLF goals: welfare and GHG reduction.

Table 2: M&S approaches regarding different simulation paradigms and PLF goals.

<table>
<thead>
<tr>
<th>Literature</th>
<th>Goal</th>
<th>M&amp;S type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Bruijnis, Hogeveen, and Stassen 2010)</td>
<td>welfare</td>
<td>DES</td>
<td>Use dynamic stochastic Monte Carlo simulation model to assess the effect of disease on income.</td>
</tr>
<tr>
<td>(Sørensen et al. 2017)</td>
<td>welfare</td>
<td>DES</td>
<td>Use dynamic mechanistic Monte Carlo simulation model for disease in pigs using R software.</td>
</tr>
<tr>
<td>(Bannink et al. 2008)</td>
<td>welfare</td>
<td>CS</td>
<td>Use mechanistic simulation model on rumen fermentation.</td>
</tr>
<tr>
<td>(Widgren et al. 2016)</td>
<td>welfare</td>
<td>CS</td>
<td>SimInf: R package.</td>
</tr>
</tbody>
</table>
We observe that most of the M&S research in livestock, are process-based which are mostly categorized as continuous simulation. The reason is that there are typically variables for which a continuous description is more natural: GHG emission, feed intake, milk production, temperature, concentration of bacteria in an infectious environment. For these variables individual counting would clearly not be feasible. Also, DES are mostly applied for improving animal welfare, rather than GHG emissions, due to the fact that most diseases have finite number of stages. Data-driven and dynamic data-driven simulation approaches has received much less attention since data availability has been a challenge in livestock sector, as elaborated in Section 5. We expect the studies in these fields to be highly rising since animal sensors are being used more widely.

## 4.4 Simulation-Based Optimization

Goals, such as profit maximization and GHG emission reduction are driving factors behind any ethical farming practice. Casting these goals as an optimization problem is natural and widely accepted. M&S, combined with optimization can be a powerful decision support approach (Ólafsson and Kim 2002). The objective and the constraints of the optimization problem are evaluated solely via simulations. Advantages
of adopting simulation-based optimization include ability to solve optimization problems without being affected to a large extend by the complexity of the system and the power to change the objective function and constraints dynamically as the system changes (Azadivar 1999). In the domain of livestock farming, we have found the following optimization approaches that have been used in combination with M&S, as shown in Table 3.

Table 3: Previous research in simulation-based optimization for livestock farming.

<table>
<thead>
<tr>
<th>Work</th>
<th>Optimization objective</th>
<th>Constraints</th>
<th>Farm type</th>
<th>Simulation done with respect to:</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Morel and Hill 2011)</td>
<td>Profit and GHG emissions</td>
<td></td>
<td>Pigs</td>
<td>Growth</td>
</tr>
<tr>
<td>(Ecim-Djuric, Topisirovic, and Buildings 2010)</td>
<td>Ventilation (energy)</td>
<td>Wind velocity and direction</td>
<td>Pigs</td>
<td>Ventilation and fluid dynamics</td>
</tr>
<tr>
<td>(Bajardi et al. 2012)</td>
<td>Reduction in epidemic spread</td>
<td>Animal movements</td>
<td>Cattle</td>
<td>Bovine movements</td>
</tr>
<tr>
<td>(Soufi, Chermitti, and Triki 2013)</td>
<td>Energy</td>
<td>Livestock shelter parameters</td>
<td>Cattle</td>
<td>Stand-alone photovoltaic systems for livestock shelters</td>
</tr>
<tr>
<td>(Fawaz et al. 2014)</td>
<td>Temperature and air quality</td>
<td>CO2, NH3 concentrations</td>
<td>Chicken</td>
<td>Thermal flow, CO2, NH3 concentrations</td>
</tr>
<tr>
<td>(Halachmi 2015)</td>
<td>Yearly turnover (production)</td>
<td>Space/culture volumes</td>
<td>Fish</td>
<td>Fish growth phases</td>
</tr>
<tr>
<td>(Mančić et al. 2016)</td>
<td>Polygeneration system configuration</td>
<td>Temperature, GHG emissions</td>
<td>Pig</td>
<td>Energy demand, polygeneration system</td>
</tr>
<tr>
<td>(Zhang et al. 2016)</td>
<td>Milk production forecast</td>
<td>Climate, Physical aspects of cows</td>
<td>Cattle</td>
<td>Yield production model, herd</td>
</tr>
<tr>
<td>(Alquisti, Ndambi, and Williams 2017)</td>
<td>Nutritional and economic feed formulation</td>
<td>Feed requirements, Dietary nutrients</td>
<td>Broiler</td>
<td>Feed formulations for broiler life cycle</td>
</tr>
<tr>
<td>(Garcia-Launay et al. 2018)</td>
<td>Feed formulation cost</td>
<td>Nutritional, GHG emissions</td>
<td>Pig, broiler, young bulls</td>
<td>Life cycle assessment</td>
</tr>
<tr>
<td>(Uyeh et al. 2018)</td>
<td>Feed formulation cost</td>
<td>Nutritional</td>
<td>Cattle</td>
<td>Feed formulations</td>
</tr>
<tr>
<td>(López-Andrés et al. 2018)</td>
<td>Environmental impact, profit, resources</td>
<td>Production limits, raw materials and energy requirements</td>
<td>Chicken</td>
<td>Raw material, energy requirements</td>
</tr>
<tr>
<td>(Michalak 2019)</td>
<td>Epidemic control</td>
<td>Time, Control strategy parameters</td>
<td>General livestock</td>
<td>Livestock population</td>
</tr>
<tr>
<td>(Zhang et al. 2020)</td>
<td>Logistics cost, GHG emission, energy consumption</td>
<td>Vehicle and sheep cost parameters</td>
<td>Sheep</td>
<td>Delivery path</td>
</tr>
<tr>
<td>(Paul et al. 2020)</td>
<td>Annual income, Annual farm balance, GHG emissions</td>
<td>Farm size, Feed balance, organic matter balance</td>
<td>Cattle</td>
<td>Bio-economic model, FarmDESIGN (Paul et al. 2015) based simulation</td>
</tr>
</tbody>
</table>

In summary, there are many works that try to optimize costs associated with livestock farms. This is because, costs can easily be formulated as an optimization objective. However, this is not the case with welfare because the overall health of livestock is harder to quantify. Sustainability of livestock farms is also another widely studied topic in the context of simulation-based optimization. It includes aspects such as optimizing energy consumption and reducing GHG emissions.

5 DATA COLLECTION AND ASSOCIATED CHALLENGES

One of the central problems in the management of information for PLF is integration and interpretation of heterogeneous data coming from different equipment and data sources. Tomic et al. (2015) mentions that mostly a 4-Level functional model has been used, that integrates the measurement level (Level 1); the interpretation level (Level 2); the integration level (Level 3); and the automation / the decision support level (Level 4) where farmers make decisions based on the system output or the system makes the decision autonomously. And they indicate that considerable additional efforts are needed to transition sensor technology together with models exploiting sensor readings into decision support systems (Level 3 and Level 4 systems) that can be used on commercial farms (Tomic et al. 2015).
As such, we argue for an integrated use of wireless sensor networks, data analytics and modelling that enable an efficient decision support system that can enable farmers to concentrate on their daily farm activities and use the data for their advantage. Figure 1 illustrates the envisioned PLF platform.

![Figure 1. Proposed Precision Livestock Farming platform](image)

Specifically, IoT devices can be installed in the farm for monitoring key parameters of:

1. stable environment (temperature, humidity, gas sensors (NOx, COx, CH4, NH3, etc.),
2. animals (accelerometer, motion sensor, weight sensor, etc.),
3. feeds (flow sensor, weight sensor, humidity sensor etc.).

A cloud-based platform can collect and analyze all the aforementioned data for providing recommendations to the livestock farming stakeholders (farmers, consultants, etc.) to take management decisions for reducing GHG emissions. In addition, blockchain technology can be used in the platform for developing different features such as data protection, data privacy, data sharing, traceability and smart contracts among the livestock farming stakeholders. Specifically, smart contracts can help livestock farming stakeholders to have contracts with better prices due to decreased GHG emissions.

There are several challenges that relate to data collection in this specific scenario as follows:

- **GHG estimation.** It is currently not possible to correctly measure GHG emission, rather estimate them as accurately as possible using the different Tiers of IPCC methodology.
- **Data sharing and interoperability.** The key challenge of integrating different livestock agricultural systems is how to deal with the heterogeneity of multiple information resources.
- **Visualization for farming stakeholders.** Many initiatives have been developed presently that boast user-friendly UIs for non-IT skilled agriculture stakeholders. However, for an end-user it is highly important to be offered already insight and decision support based on data analytics. This is an end-goal of implementing the platform presented in Figure 1.

6 CONCLUSIONS

We have provided an overview of the need and use of Modelling and Simulation to support the main goals of Precision Livestock Farming. We have identified the main goals as enhancement of animal welfare and reduction of GHG emissions. Nowadays, with the availability of advanced sensing technologies, data has become more available, and this is also slowly changing the way in which traditional simulation is performed, yielding new and more data-driven approaches. We scoped the existing approaches and categorized them by simulation paradigm and goals, to provide an exhaustive overview and a tool of deciding on a suitable approach with respect to a given problem. We, furthermore, discussed the challenges associated with the data collection processes, and a possible solution. PLF opens doors for more advanced
and sophisticated approaches and fully transforms the traditional livestock farming processes, especially when combined with M&S and advanced data analytics approaches. It could prove to be an important piece of the puzzle yielded by the challenges associated with the climate changes and sustainable food production.

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