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A hierarchical Markov decision process modeling feeding and marketing decisions of growing pigs

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ABSTRACT

Feeding is the most important cost in the production of growing pigs and has a direct impact on the marketing decisions, growth and the final quality of the meat. In this paper, we address the sequential decision problem of when to change the feed-mix within a finisher pig pen and when to pick pigs for marketing. We formulate a hierarchical Markov decision process with three levels representing the decision process. The model considers decisions related to feeding and marketing and finds the optimal decision given the current state of the pen. The state of the system is based on information from on-line repeated measurements of pig weights and feeding and is updated using a Bayesian approach. Numerical examples are given to illustrate the features of the proposed optimization model.

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1. Introduction

In production systems of growing pigs, feeding is the most important operation and has a direct influence on the cost and the quality of the meat. Another important operation is the timing of *marketing*. It refers to a sequence of culling decisions until the production unit is empty. As a result the profit of the production unit is highly dependent on the feeding cost and on good timing of marketing, i.e. decisions about feeding and marketing have a direct impact on profit.

In a production system of growing/finishing pigs (Danish standards), the animals may be considered at different levels: herd, section, pen, or animal. The herd is a group of sections, a section includes some pens, and a finisher pen involves some animals (usually 15–20). New piglets are transferred to a weaner unit approx. four weeks after birth, and they stay for approx. eight weeks until they weigh approx. 30 kilograms. The pigs are then moved to a finisher pen where they grow until marketing (9–12 weeks). In the finisher pen, the farmer should determine which pigs should be selected for slaughter (individual marketing). The reward of marketing a pig depends on the unit meat price of the carcass weight and the leanness of the pig. The meat price is highest if the carcass weight of the pig lies in a specific interval. Next, after a sequence of individual marketings, the farmer must decide when to *terminate* (empty) the rest of the pen. Terminating a pen means that the remaining pigs in the pen are sent to the slaughterhouse (in one delivery) and after cleaning the pen, another group of piglets (each weighing approx. 30 kilograms) is inserted into the pen and *the production cycle* is repeated. That is, the farmer must time the marketing decisions while simultaneously considering the carcass weight in relation to the best interval, the leanness, and the length of the production cycle. For an extended overview over pig production of growing pigs, see Pourmoayed and Nielsen (2014a).

The growth and leanness of the pigs will be highly dependent on the feed given. Phase feeding is a common method used in the production of the growing pigs. In the finisher pen the growing period typically includes 3 or 4 phases and each phase involves a predefined *feed-mix* which is a mixture of different ingredients (barley, soy, maize, etc.). A relevant decision is when to change the current feed-mix (transition to a new phase) and what type of feed-mix to use in the next phase.

Since the choice of feed-mix affects the pigs' growth, a specific feeding strategy has an impact on the marketing strategy. That is, the economic optimization of feeding and marketing decisions is interrelated and requires a simultaneous analysis. Consequently, a sequential decision model is needed that considers both feeding and marketing decisions. To the best of our knowledge, there are only a few studies that take into account these decisions simultaneously (Niemi, 2006; Sirisatien, Wood, Dong, & Morel, 2009). However, these studies consider the problem at animal level and do not take into account the inhomogeneity of animals in growth and feed intake. The aim of this paper is to close this gap and consider the problem at pen level instead.

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In this paper we formulate a hierarchical Markov decision process which takes into account decisions related to feeding and marketing of growing pigs at pen level. We assume that the production is cyclic, i.e. when the pen is emptied, not only a regular state transition takes place, but rather the process (the current batch of pigs) is restarted.

The model considers time series of pig weights and feeding obtained from online monitoring, e.g. from a set of sensors in the pen. A Bayesian approach is used to update the state of the system such that it contains the relevant information based on the previous measurements. More precisely, two state space models for *Bayesian forecasting* (West & Harrison, 1997) are used to update the estimates of live weights and feed intake on a weekly basis.

The structure of the paper is as follows. First, Section 2 gives a short literature review. Second, a detailed description of the optimization model is given in Section 3. Next, Section 4 presents the statistical models which are embedded into the model. In Section 5, numerical examples are considered to show the functionality of the proposed optimization model. Finally, conclusions and directions for further research are given in Section 6.

2. Literature review

Due to the dynamic nature of the production environment of growing pigs, the marketing and feeding decisions are sequential, complex and hard to optimize. Various models have been considered to deal with this complexity.

Some studies consider only the marketing decisions. Chavas, Kliebenstein, and Crenshaw (1985) applied the concepts of optimal control theory to find the optimal time of marketing of individual animals. Jørgensen (1993) used a dynamic programming approach to optimize a given heuristic framework for delivering the pigs to the slaughterhouse. Boland, Preckel, and Schinckel (1993) considered the optimal slaughter pig marketing problem under different pricing models and for each pricing system, they found the optimal slaughter weight. Kure (1997) considered the problem at batch level and used the replacement theory concepts and a recursive dynamic programming method to determine the optimal time of marketing the pigs. Toft, Kristensen, and Jørgensen (2005) optimized both marketing and treatment decisions (e.g. regarding vaccination for disease problems) using a *hierarchical Markov decision process* (*HMDP*). Boys, Li, Preckel, Schinckel, and Foster (2007) implemented a simulation approach to determine the best marketing strategy to utilize full truck capacity for delivering the pigs to the packers. In the study by Ohlmann and Jones (2008), a mixed integer programming model was proposed to find the best marketing strategy under an annual profit criterion. Kristensen, Nielsen, and Nielsen (2012) suggested a two-level HMDP to find the best marketing strategy according to the data from an online monitoring system.

Other studies focus on sequential feeding decisions, i.e. finding the best strategy for choosing the appropriate feed-mix during the growing period of animals. One example is Glen (1983) who proposed a dynamic programming approach to determine the sequence of feed-mixes in the production unit. In the study by Boland, Foster, and Preckel (1999), a linear programming approach was used to specify the optimal time of changing the feed-mix and also the optimal nutrient ingredients of the feed-mix. A genetic algorithm was applied by (Alexander, Morel, & Wood, 2006, chap. 2) to find the best nutrient components of each feed-mix.

Only a few studies take both marketing and feeding decisions into account. Niemi (2006) used a mechanistic function to model the animal growth trend during the growing period. Niemi (2006) further applied a stochastic dynamic programming method to find the best nutrient ingredients and also the best time of marketing. In the study by Sirisatien et al. (2009), a genetic algorithm was used. Each iteration resulted in a set of feeding schedules followed by the optimal values of the nutrient ingredients and feeding period. Both studies considered the problem at animal level and did not take into account the inhomogeneity of animals with respect to growth and feed conversion rate.

Markov decision models are a well-known modeling technique within animal science used to model livestock systems. See for instance Rodriguez, Jensen, Pla, and Kristensen (2011) and Nielsen, Jørgensen, Kristensen, and Østergaard (2010). For a recent survey see Nielsen and Kristensen (2015), which cites more than 100 papers using (hierarchical) Markov decision processes to model and optimize livestock systems. An HMDP is an extension of a semi Markov decision process (semi-MDP) where a series of finite-horizon semi-MDPs are combined into one process at the founder level called the main process (Kristensen, 1988; Kristensen & Jørgensen, 2000). As a result the state space at the founder level can be reduced and larger models can be solved using a modified policy iteration algorithm under different criteria (Nielsen & Kristensen, 2015). Modeling the problem using an HMDP compared to a semi-MDP contributes to reducing the *curse of dimensionality*, since the total number of state variables can be decreased. Moreover, the total number of states at the founder level is lower (i.e. the matrix which must be inverted in the modified policy iteration algorithm is much smaller).

A *state space model* (*SSM*) (West & Harrison, 1997) is a statistical model which may be used to transform large datasets obtained using online sensors into the required information about the production process. An SSM consists of a set of latent variables and a set of observed variables. At a specified point in time the conditional distribution of the observed variables is a function of the latent variables specified via the observation equations. The latent variables change over time as described via the system equations. The observations are conditionally independent given the latent variables. Thus the estimated value of the latent variables at a time point may be considered as the state of the system, and with Bayesian forecasting (the Kalman filter) we can estimate the latent variables/real state of the system via the observed variables. Examples of SSMs applied to agricultural problems are Bono, Cornou, and Kristensen (2012), Bono, Cornou, Lundbye-Christensen, and Kristensen (2013) and Cornou, Vinther, and Kristensen (2008). Moreover, an SSM can be discretized and embedded into an HMDP (Nielsen, Jørgensen, & Højsgaard, 2011).

3. Model description

Our pig marketing and feeding problem is modeled using a *hierarchical Markov decision process* (*HMDP*) with three levels. A short introduction to HMDPs is given below. As techniques from both statistical forecasting and operations research are used, consistent notation can be hard to specify. To assist the reader, Appendix A provides an overview.

An HMDP is an extension of a semi-MDP where a series of finite-horizon semi-MDPs are combined into one infinite time-horizon process at the founder level called the *founder process* (Kristensen & Jørgensen, 2000). The idea is to expand the stages of a process to so-called *child processes*, which again may expand stages further to new child processes leading to multiple levels. At the lowest level the HMDP consists of a set of finite-horizon semi-MDPs (see e.g. Tijms, 2003, chap. 7). All processes are linked together using jump actions (see Fig. 1).

A *finite-horizon semi-MDP* considers a sequential decision problem over $\mathcal{N}$ *stages*. Let $\mathbb{I}_n$ denote the finite set of system states at stage n. When *state* $i \in \mathbb{I}_n$ is observed, an *action* a from the finite set of allowable actions $\mathbb{A}_n(i)$ must be chosen, and this decision generates *reward* $r_n(i, a)$. Moreover, let $u_n(i, a)$ denote the *stage length* of action a, i.e. the expected time until the next decision epoch (stage $n + 1$) given action a and state i. Finally, let $\Pr(j \mid n, i, a)$ denote the *transition probability*

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