The PigIT Closing Conference

Book of Presentations II
Publications of PigIT

Tuesday, November 13th, 2018, University of Copenhagen

PigIT Report No. 11 • November 2018

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This note is also available on www at URL:
http://www.pigit.net/publications/PigIT-Report11.pdf

Centre for Herd-oriented Education, Research and Development
Department of Veterinary and Animal Sciences
University of Copenhagen

Contents

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Chapter 1

The Closing Conference

1.1 Welcome

It is a great pleasure to welcome our international and Danish connections from science and industry to this event where we share the results and experiences of the seven year research project within the field of precision pig farming.

The PigIT project, with the full title *Improving welfare and productivity in growing pigs using advanced ICT methods*, is a strategic research alliance supported by the Danish Council for Strategic Research. It was initiated in 2012 and was, originally, planned to run for five years. It has later been extended by two years.

The partners of the alliance are University of Copenhagen, Aarhus University and the Danish Pig Research Centre. The private companies TNM A/S, Skov A/S and AgroSoft A/S (from 2014) have been affiliated partners.

The scientific objectives of the project have been to develop and improve methods for

1. Model based production and welfare monitoring, and
2. Model based decision support

The themes of the program reflect those two objectives, and the day concludes with perspectives for the future.

1.2 Program

1.2.1 Arrival and registration

The registration desk opens at 9:30 where also a cup of coffee is served.

1.2.2 Theme 0: PigIT - motivation and core concepts

Chair: *Lene Juul Pedersen*

10:00 The ideas behind the PigIT project. *Anders Ringgaard Kristensen*, University of Copenhagen

1.2.3 Theme 1: Model based production and welfare monitoring

Chair: *Lene Juul Pedersen*

10:30 A dynamic approach to monitoring of growth in finishers. *Anna Helena Stygar*, University of Copenhagen (present affiliation: Luke, Finland)

10:50 Automatic learning and pattern recognition using sensor data. *Dan Børge Jensen*, University of Copenhagen

11:20 Coffee break

1.2.4 Theme 1 (continued): Model based production and welfare monitoring

Chair: *Dan Børge Jensen*

11:40 Spatial modeling of drinking patterns as a tool for reducing alarms in pig production. *Katarina Nielsen Dominiak*, University of Copenhagen (present affiliation: SEGES, The Pig Research Centre)

12:10 Behavioral changes preceding tail biting and pen fouling in slaughter pig pens. *Lene Juul Pedersen*, Aarhus University

12:30 Using machine learning to predict tail-biting, fouling and diarrhea in pigs. *Yuvraj Domun*, Harper-Adams, United Kingdom

12:50 Lunch

1.2.5 Theme 2: Model based decision support

Chair: *Anders Ringgaard Kristensen*

13:50 Models and methods for optimization of pig production in a stochastic environment. *Reza Pourmoayed*, Aarhus University (present affiliation: Grundfos)

14:20 From raw data to optimal sow replacement decisions - an integrated solution. *Jeff Hindsborg*, University of Copenhagen

14:40 Coffee break

1.2.6 Theme 3: Where to go from here

Chair: Nils Toft

15:00 The IQinAbox project. *Thomas Nejsum Madsen*, Nejsum Aps

15:20 Ambitions for machine vision. *Dan Børge Jensen*, University of Copenhagen

15:40 Plenary discussion. *All presenters*

16:00 Closing

Chapter 2

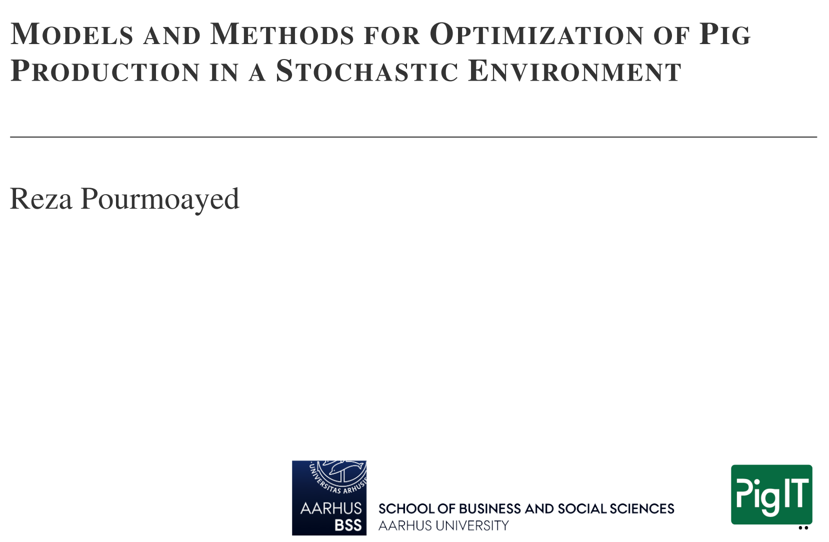
Book of presentations II

2.1 Theme 2: Model based decision support

Chair: Anders Ringgaard Kristensen

2.1.1 Models and methods for optimization of pig production in a stochastic environment

Presentation by Reza Pourmoayed

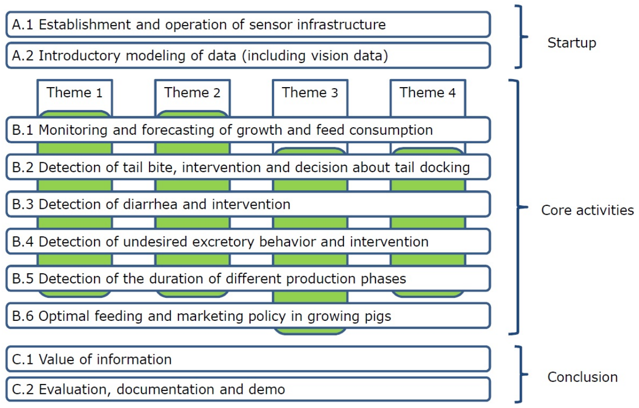


Agenda

1. Background
2. Paper I
3. Paper II
4. Paper III
5. Wrap-up

Background

PigIT Project

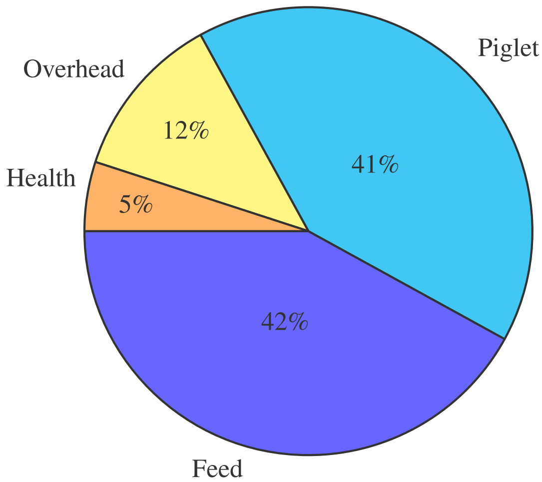


Main focus of the PhD project (B.6)

Stochastic optimization models focusing on feeding and marketing decisions in finishing units.

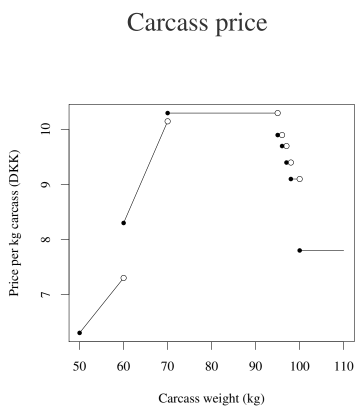
Finishing unit (costs)

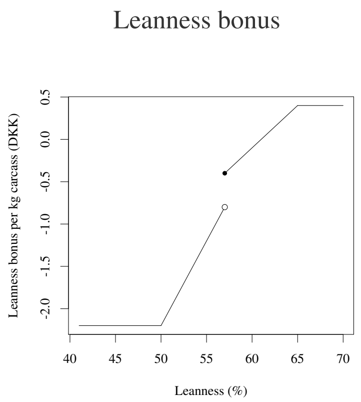
Distribution of production costs per finisher pig (?):



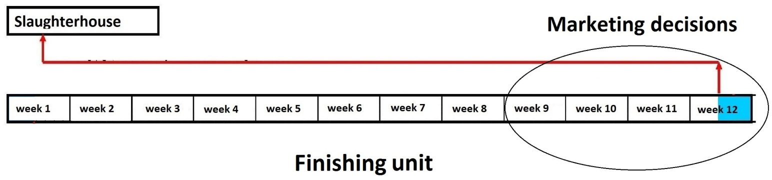
Finishing unit (price function)

Price of finisher pig per kg carcass weight:



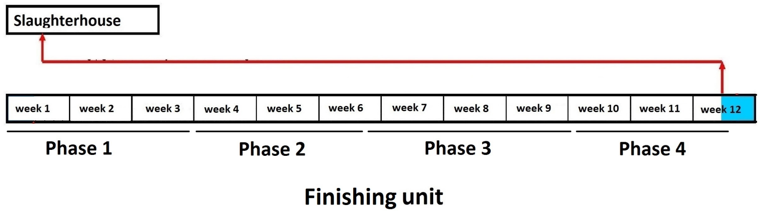


Marketing decisions



- In the last weeks of growing period, which animals should be culled and which animals should be kept in the pen (individual marketing)?
- When should the pen/section be terminated (all the remaining pigs are culled)?

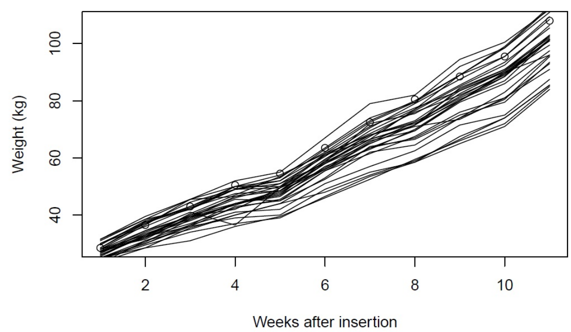
Feeding decisions



- During the growing period, when should a new phase start and which feed-mix should be used?

Main challenges

- Feeding and marketing decisions should often be taken simultaneously.
- Weekly fluctuations of pork, feed, and piglets prices in market.
- How to link decisions between animal, pen, section an herd level.
- Uncertainty of weight information.



Research papers

Paper I: A hierarchical Markov decision process modeling feeding and marketing decisions of growing pigs.

Paper II: Slaughter pig marketing under price fluctuations.

Paper III: An approximate dynamic programming approach for sequential pig marketing decisions at herd level.

Methods

Operations Research

- Papers I & II: Hierarchical Markov decision process
- Paper III: (Semi) Markov decision process; approximate dynamic programming

Statistics

- Papers I, II & III: State space models with Bayesian updating
- Paper II: Random regression model

Paper I

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

Reza Pourmoayed and Lars Relund Nielsen

CORAL, Department of Economics and Business Economics, Aarhus University, Fuglesangs Allé 4, DK-8210 Aarhus V, Denmark.

Anders Ringgaard Kristensen

HERD, Department of Large Animal Sciences, University of Copenhagen, Grønnegårdsvej 2, DK-1870 Frederiksberg C, Denmark.

Published in European Journal of Operational Research, 250(3):925-938, 2016.

Contributions

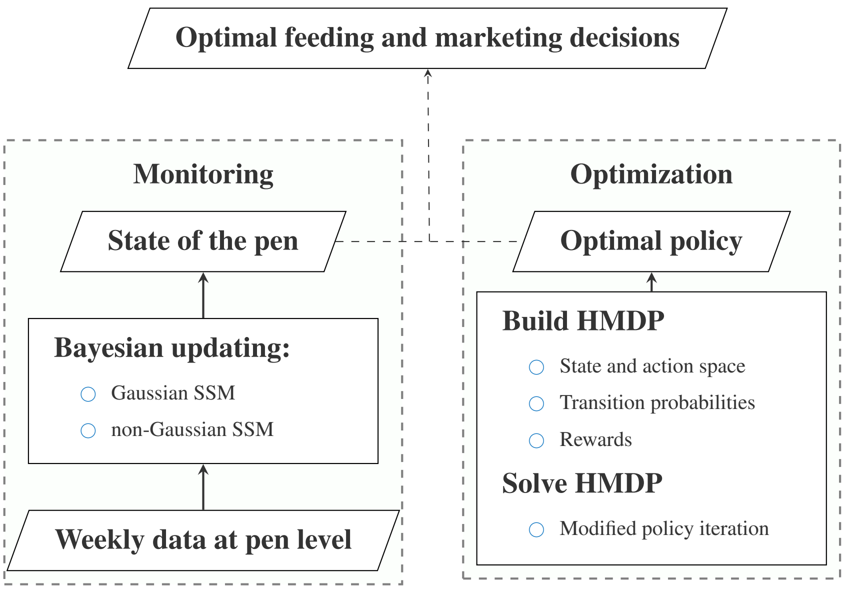
Contributions

- Optimization of feeding and marketing decisions at pen level.
- Bayesian updating of on-line weight and feed intake data.

Methods

- Optimization model: Three-level HMDP.
- Statistical models: Gaussian and non-Gaussian SSMs.

Decision model



Decision model

Optimal feeding decisions

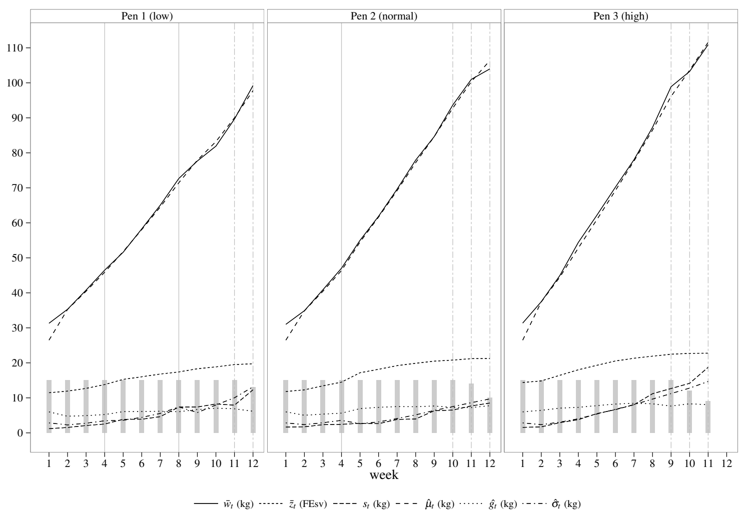
- Keep the current feed-mix
- Change the current feed-mix
- Find the best feed-mix for the next phase of feeding

Optimal marketing decisions

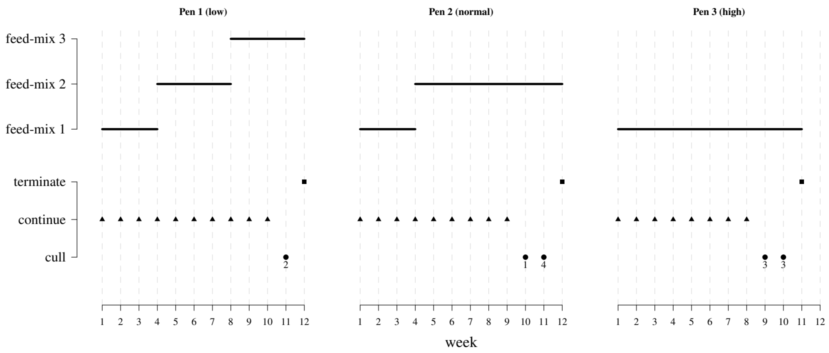
- Market q heaviest pigs for slaughter
- Terminate the pen.
- Continue the production process without marketing.

Results - 3 Pens (low, normal and high growth)

- Average growth rate of pigs in Pen 2 is normal (6 kg per week).
- In Pens 1 and 3, pigs grow 20% slower and faster than Pen 2.



Results - 3 Pens (low, normal and high growth)



Feed-mix	Initial average growth (kg)	price (DKK/FEsv)
1	5.8	1.8
2	6.3	1.88
3	6.8	1.96

Results - Sensetivity analysis

Scenario group	Parameter change	Gross margin per week (DKK)
Basic	none	71.349
Group 1 - starting time of marketing period	$t^{\min} = 8$	71.355
	$t^{\min} = 10$	71.249
	$t^{\min} = 11$	70.428
Group 2 - maximum length of growing period	$t^{\max} = 11$	34.155
	$t^{\max} = 13$	92.618
	$t^{\max} = 14$	104.644
	$t^{\max} = 15$	110.884
Group 3 - feed-mix unit cost	10% increase	27.444
	10% decrease	116.064

PAPER II

Slaughter pig marketing under price fluctuations

Reza Pourmoayed and Lars Relund Nielsen

CORAL, Department of Economics and Business Economics, Aarhus University, Fuglesangs Allé 4, DK-8210 Aarhus V, Denmark.

Submitted to Annals of Operations Research

Contributions

Contributions

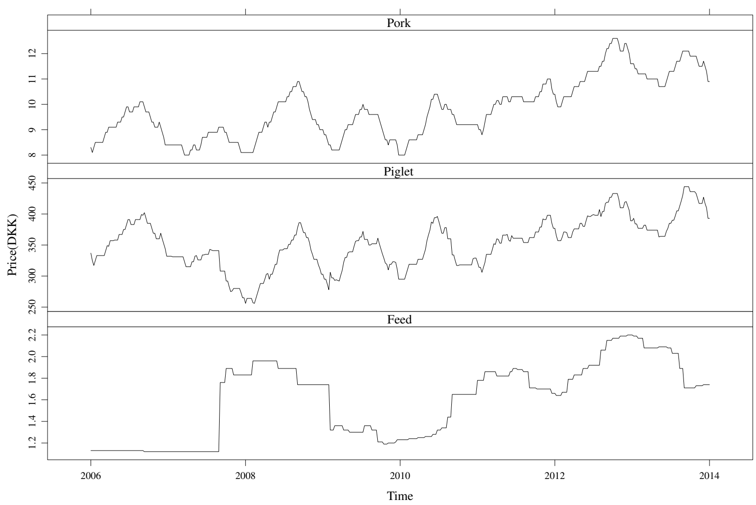
- Optimization of marketing decisions under price fluctuations at pen level.
- Bayesian forecasting of pork, feed and piglet prices.

Methods

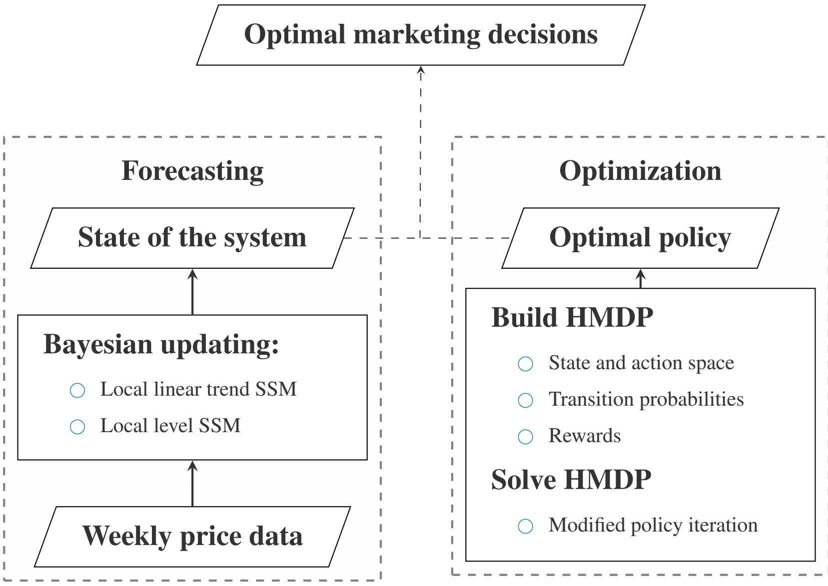
- Optimization model: Two-level HMDP.
- Statistical models: Three Gaussian SSMs; random regression model (RRM).

Price fluctuations

- Pork, piglet, and feed prices can fluctuate in every week.

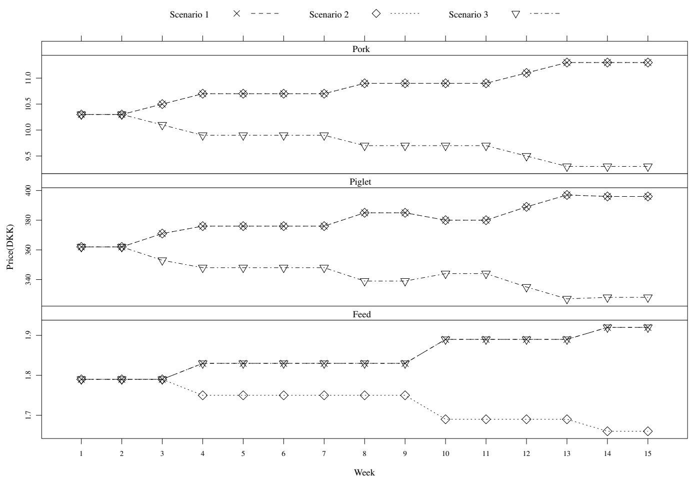


Decision model

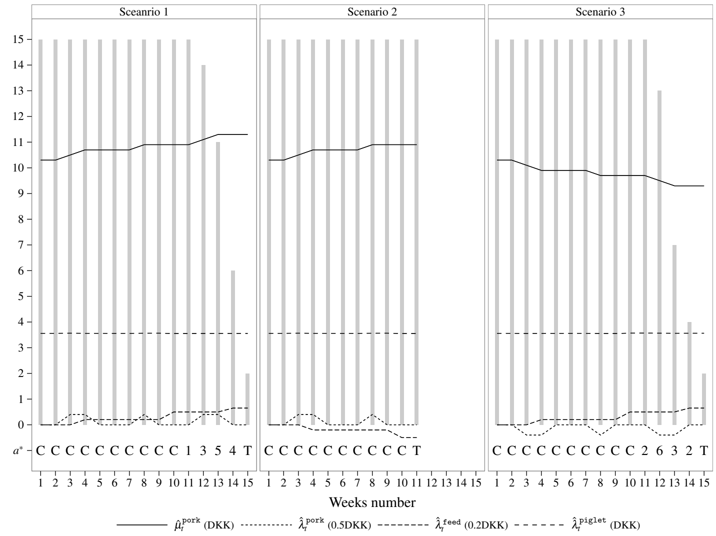


Results - 3 Scenarios

Scenario 1: Favourable trend of pork price and unfavourable trends of feed and piglet prices
Scenario 2: Favourable trends of pork and feed prices and unfavourable trend of piglet price.
Scenario 3: Unfavourable trends of pork and feed prices and favourable trend of piglet price.



Results - 3 Scenarios



Results - Value of price information

What is the value of considering price fluctuations in marketing decisions of growing pigs?

- Expected reward per week for the optimal policy: $g^* = 157.2$ DKK
- Expected reward per week for a policy with given constant prices (g)
- Value of information (VOI): $VOI = g^* - g$

Price setting (PS)	Pork price	Feed price	Piglet price	VOI (DKK)
1	10.8	1.85	376	41.07
2	10.8	1.55	376	41.29
3	10.8	2.15	376	43.91
4	9.4	1.85	327	41.26
5	12	1.85	418	40.25
6	12	2.15	418	43.75
7	9.4	1.55	327	55.21

PAPER III

An approximate dynamic programming approach for sequential pig marketing decisions at herd level

Reza Pourmoayed

CORAL, Department of Economics and Business Economics, Aarhus University, Fuglesangs Allé 4, DK-8210 Aarhus V, Denmark.

Submitted to European Journal of Operational Research

Contributions

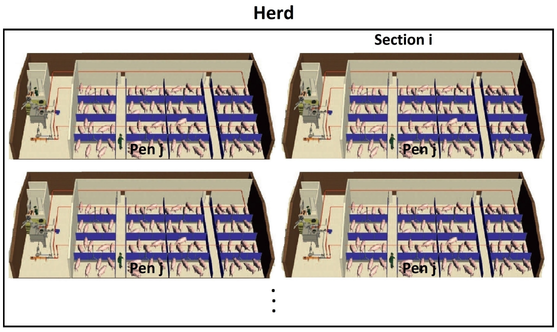
Contributions

- Optimization of marketing decisions at herd level.
- Solving a high dimensional MDP using an approximate dynamic programming method.

Methods

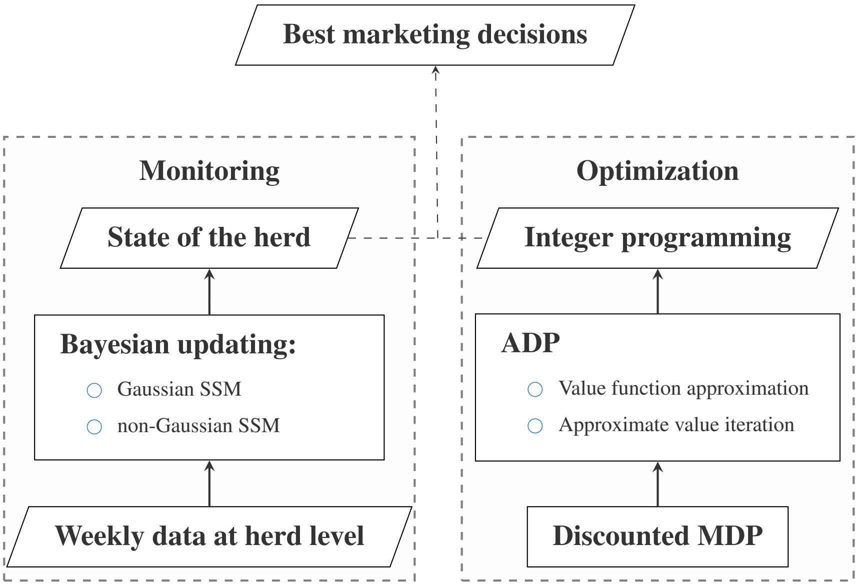
- Optimization model: Discounted infinite-horizon MDP; approximate dynamic programming (ADP).
- Statistical models: SSMs in Paper I.

Marketing decisons



- Weight and feed intake data are observed in all pens.
- Production process in each section is independent of other sections.
- Cross-level constraints:
  - Termination at section level
  - Transportation at herd level

Decision model



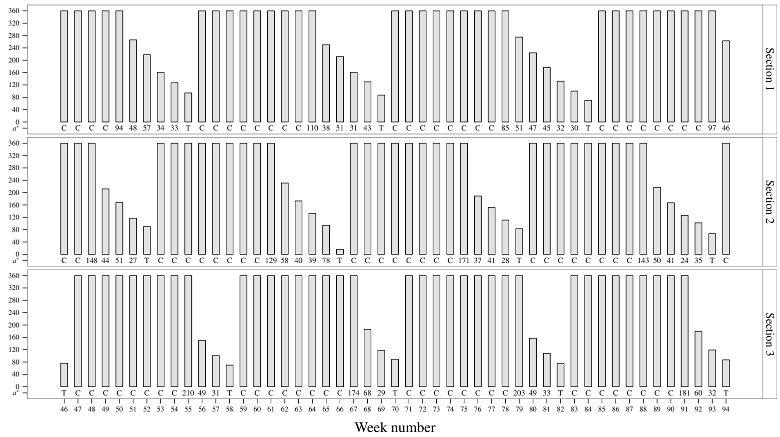
Decision model

Best marketing decisions

- Pen level: Number of heaviest pigs marketed from each pen.
- Section level: Terminating the section or continuing the production process.
- Herd level: Number of trucks needed to send the culled pigs to the abattoir.

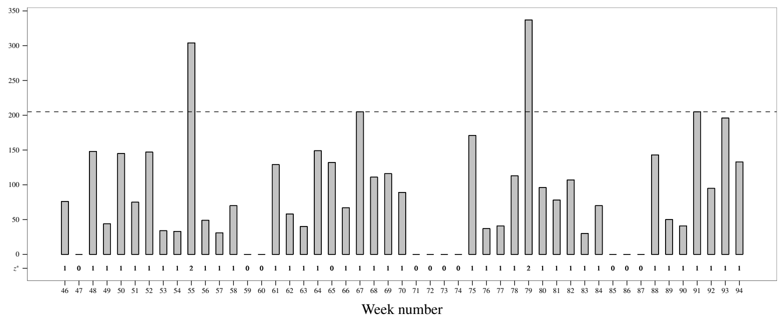
Results - Marketing decisions at herd level

- Average growth rate of pigs in Section 2 is normal (6 kg per week).
- In Sections 1 and 3, pigs grow 10% slower and faster than Section 2.



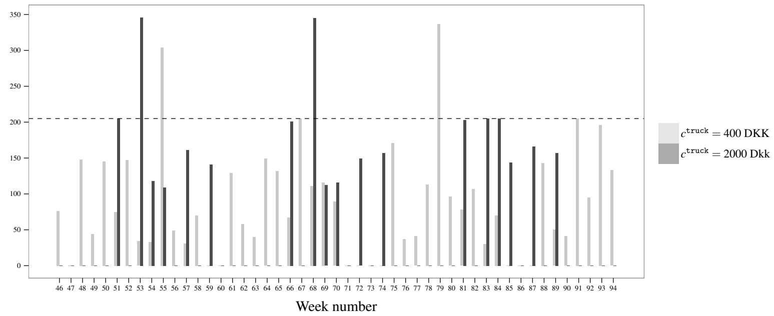
Results - Marketing decisions at herd level

- Total number of culled pigs in the herd



Results - Marketing decisions at herd level

- Effect of transportation cost on marketing policy



Results - ADP compared to other marketing policies

Marketing policy obtained by ADP is compared with the following polices:

- Myopic policy (M):
- All-In All-Out policies with lengths 9 to 15 weeks.
- Full truck capacity policy (FTC).

Results - ADP compared to other marketing policies

Policy	ADP	M	FTC	All-In All-Out	
				9	10
Av. discounted reward per week	2072 ± 45.5	1078 ± 11.1	1830 ± 103	470 ± 11.9	1398 ± 10.3
Av. length of production cycle	11.8 ± 0.01	10 ± 0	11.6 ± 0.06	9 ± 0	10 ± 0
Number of production cycles	30.5 ± 0.14	36 ± 0	31.3 ± 0.28	39 ± 0	36 ± 0
% of truckload capacity utilized	76 ± 1	75 ± 0	88 ± 0	87 ± 0	87 ± 0
Number of trucks sent to abattoir	73.7 ± 1	84 ± 0	63.6 ± 0.5	84 ± 0	72 ± 0

Policy	All-In All-Out				
	11	12	13	14	15
Av. discounted reward per week	1831 ± 7.6	1881 ± 6.7	1679 ± 4.6	1365 ± 4	1014 ± 3.9
Av. length of production cycle	11 ± 0	12 ± 0	13 ± 0	14 ± 0	15 ± 0
Number of production cycles	33 ± 0	30 ± 0	27 ± 0	27 ± 0	24 ± 0
% of truckload capacity utilized	87 ± 0	87 ± 0	87 ± 0	87 ± 0	87 ± 0
Number of trucks sent to abattoir	66 ± 0	60 ± 0	54 ± 0	54 ± 0	48 ± 0

Results - Sensitivity analysis

- Sensitivity analysis for truckload capacity and feed and pork prices (for a normal herd)

Scenario group	Parameter change	Av. descounted reward per week (DKK)
Basic	none	2072 ± 45
Group 1 - truckload capacity	$k^{\texttt{truck}} = 102$	1933 ± 90
	$k^{\texttt{truck}} = 155$	2033 ± 83
	$k^{\texttt{truck}} = 255$	2106 ± 44
	$k^{\texttt{truck}} = 305$	2124 ± 29
Group 2 - feed price	20% increase	1226 ± 54
	20% decrease	2981 ± 59
Group 3 - pork price	20% increase	3746 ± 18
	20% decrease	-1278 ± 3

Wrap-up

Wrap-up

- Decision models to assist the farmer to choose the best feeding and marketing policy at farm.
- Monitoring and forecasting models are based on Bayesian updating applied to weight and price data.
- Optimization models are based on Markov models and their focus is on the economical aspects of the problem.
- C++ and R are the main programming languages used to code the algorithms. Codes are available at GitHub.

2.1.2 From raw data to optimal sow replacement decisions - an integrated solution

Presentation by Jeff Hindsborg

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Introduction

Background

- Sow replacement model[1]
  1. Applied in the context of herd analysis
  2. Experiences

     Sow valuation → Evaluate culling strategy → Quantifying losses → Assess the impact of improving the culling strategy
  3. Calibration requires specialized knowledge

Objective

- Develop a an integrated ITC tool to improve culling strategies
  1. Automatic calibration of the replacement model to the individual herd
  2. Direct integration with commercial management information software
  3. Design a user-friendly interface
  4. Performance of each individual animal

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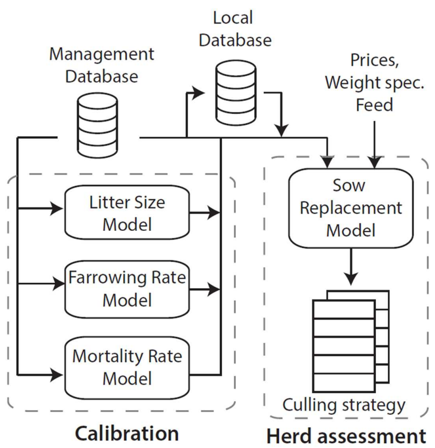
System Design



Outcome

- Current animals
- Culled animals
- (Dynamic monitoring system)

Dynamic Monitoring System

- Herd specific trends using Dynamic Linear Models[2]
  - State-space based dynamic regression

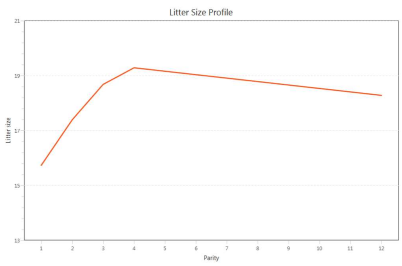
    $Y_t = \boldsymbol{F}_t^T \boldsymbol{\theta}_t + \varepsilon_t$ (observation equation)

    $\boldsymbol{\theta}_t = \boldsymbol{G}_t \boldsymbol{\theta}_{t-1} + \boldsymbol{\omega}_t$ (evolution equation)

  where
    - $\boldsymbol{\theta}_t$ is the state vector,
    - $\boldsymbol{F}_t$ is the regression vector
    - $\boldsymbol{G}_t$ is the state matrix
  - Updated in line with new data being available
  - Provide a dynamic monitoring system
    - Also provides useful estimates not used for calibration

Results

- Dynamic monitoring system



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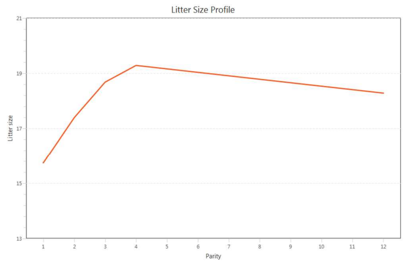
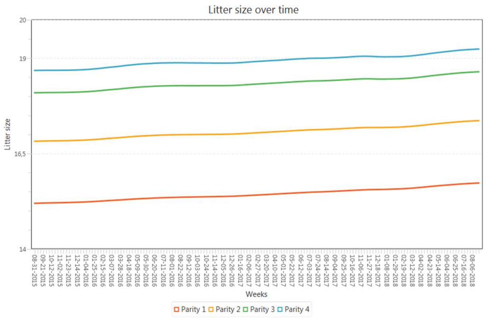
Results

- Dynamic monitoring system





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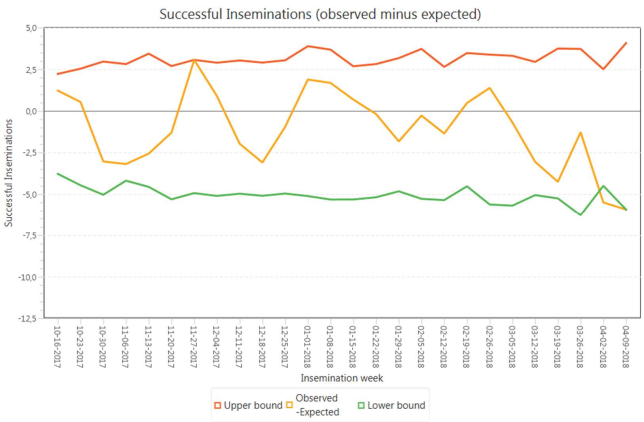
Results

- Dynamic monitoring system



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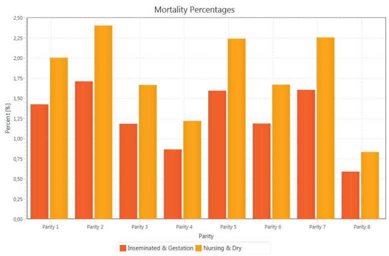
Results

- Dynamic monitoring system



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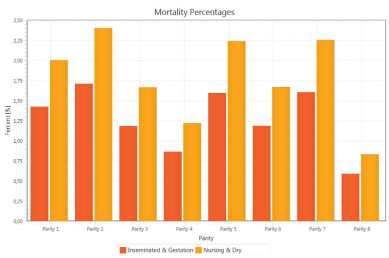
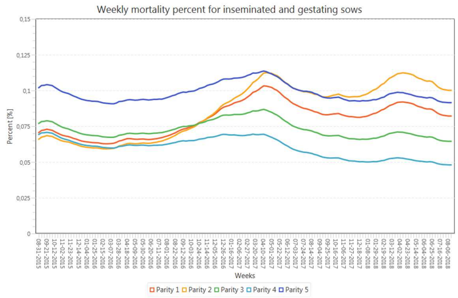
Results

- Dynamic monitoring system





Demonstration

1. **Settings**
   - Calibration (via dynamic models)
   - Specifications of parameters
2. **Herd**
   - Sows currently on the farm
   - Sorting and exporting capabilities
3. **Culling**
   - Sows no longer in production
   - Estimate historical losses due to non-optimal culling
4. **Plot**
   - Production estimates from the dynamic models

Summary

- Software tool based on raw data:
  - Decision support in sow replacement
  - Assessing the culling strategy
  - Monitor progress in various parameters in real-time

- Software freely available at www.pigit.ku.dk/SoLiv
  - In Danish and English
  - User-defined currency
  - Compatible with
    - AgroSoft WinPig (.NET version)
    - Cloudfarms
    - Demo is available

Summary

- Financed by

PigIT and Promilleafgiftsfonden (Production levy foundation)

- Bibliography

[1]

Kristensen, A.R. & T.A. Søllested. 2004. A sow replacement model using Bayesian updating in a three-level hierarchic Markov process. I. Biological model. *Livestock Production Science 87*, 13-24.

Kristensen, A.R. & T.A. Søllested. 2004. A sow replacement model using Bayesian updating in a three-level hierarchic Markov process II. Optimization model. *Livestock Production Science 87*, 25-36

Rodríguez, S.V., T.B. Jensen, L.M. Plà & A.R. Kristensen. 2011. Optimal replacement policies and economic value of clinical observations in sow herds. *Livestock Science 138*, 207-219.

[2]

Claudio Bono, Cecile Cornou, Kristensen A.R. 2012. Dynamic production monitoring in pig herds I: Modeling and monitoring litter size at herd and sow level. *Livestock Science 149, 289-300.*

Claudio Bono, Cecile Cornou, Søren Lundbye-Christensen, Kristensen A.R. 2013. Dynamic production monitoring in pig herds II: Modeling and monitoring farrowing rate at herd level. *Livestock Science 155, 92-102.*

Claudio Bono, Cecile Cornou, Kristensen A.R. 2014. Dynamic production monitoring in pig herds III: Modeling and monitoring mortality rate at herd level. *Livestock Science 168, 128-138.*

2.2 Theme 3: Where to go from here

Chair: Nils Toft

2.2.1 The IQinAox project

Presentation by Thomas Nejsum Madsen

IQinAbox

The project

- IQinAbox is a commercial enterprise
  - monitoring and management of growing pigs
  - 4 year iterative development process NT3
- Partners:
  - IQinAbox (lead: Thomas Nejsum Ma NT5 n & NT4 Toft)
  - University of Copenhagen (lead: Anders Ringgaard Kristensen)
  - SEGES – Pig Research Centre (lead: Jens Vinther)
- Budget: 20+ mio. Dkr.
- GUDP grant: 11 mio. Dkr. (Ministry of and Environment and Food of Denmark)

2

Slide 2

NT3 En vigtig pointe er at en del af det her software og modeller fejler fordi alt er baseret på nogle meget få og måske ikke ret realistiske datasæt. Derfor er det vigtigt at komme ud med en første version hurtigt og så lære af den.
Nils Toft; 12-11-2018

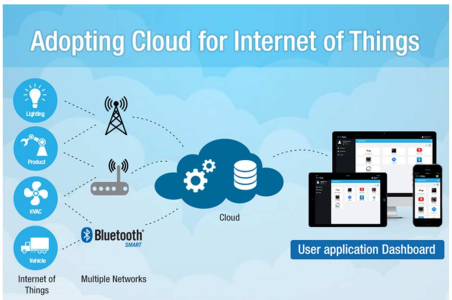
NT4 Det er nok også relevant at fremhæve vores adaptive tilgang til håndtering af alarmer.
Nils Toft; 12-11-2018

NT5 Hvis vi ligesom skal være næste skridt fra PigIT, så er ovenstående vel nogen af de vigtigste pointer? Og nogle af de centrale læringspunikter fra PigIT, som vi så tager med videre over i IQinAbox.
Nils Toft; 12-11-2018

IQinAbox

The concept NT6

- We use technologies from the production industry in combination with results from Herd Management research (e.g. PigIT)
- IoT based sensors
- Cloud based data analysis and Machine Learning



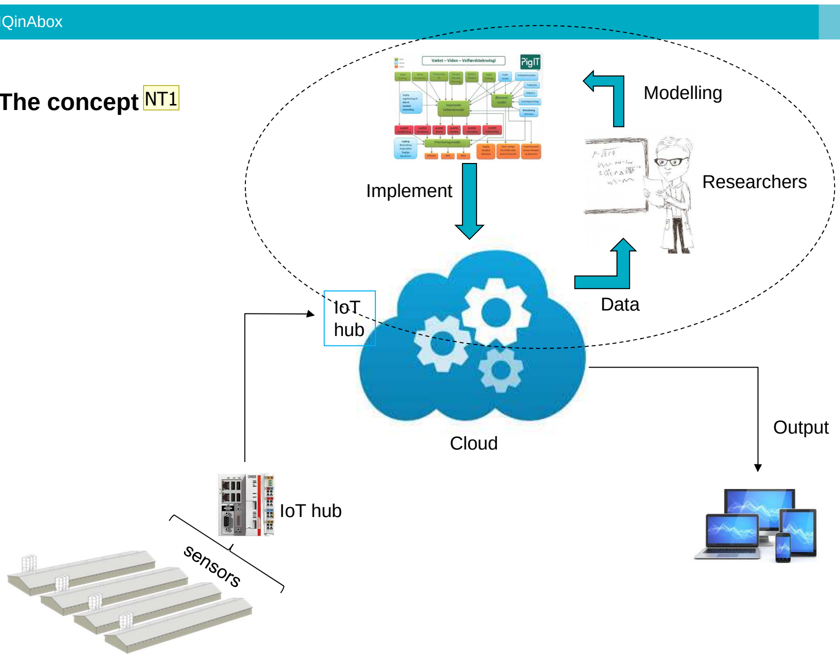
3

Slide 3

NT6 Og det er smart fordi det holder prisen nede - Starter ikke fofra med at tænke over alle de ting der gør svineproduktion unik, men arbejder ud fra e
tese om at der er en masse lighedspunkter over til problemer man allerede har set på i industrien.
Nils Toft; 12-11-2018

IQinAbox

The concept NT1



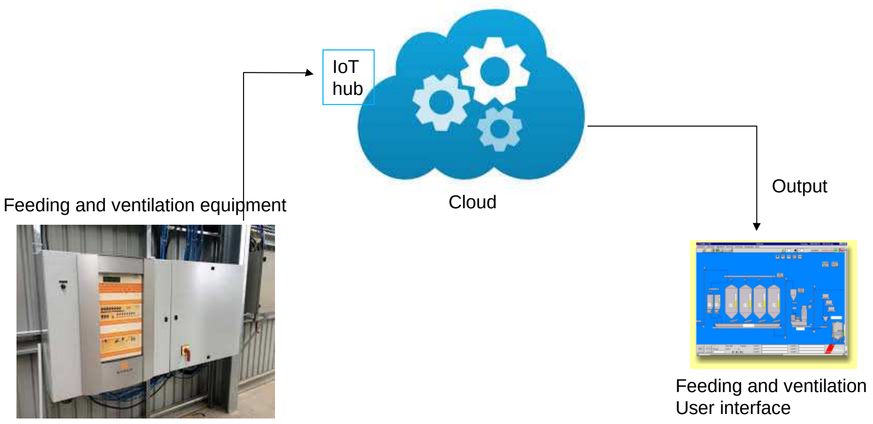
4

Slide 4

NT1 Jeg tænker at du bør vise feedback mekanismen, på den her slide og snakke om den. Det er jo en ret central del af IQinAbox projektet.
Nils Toft; 12-11-2018

IQinAbox

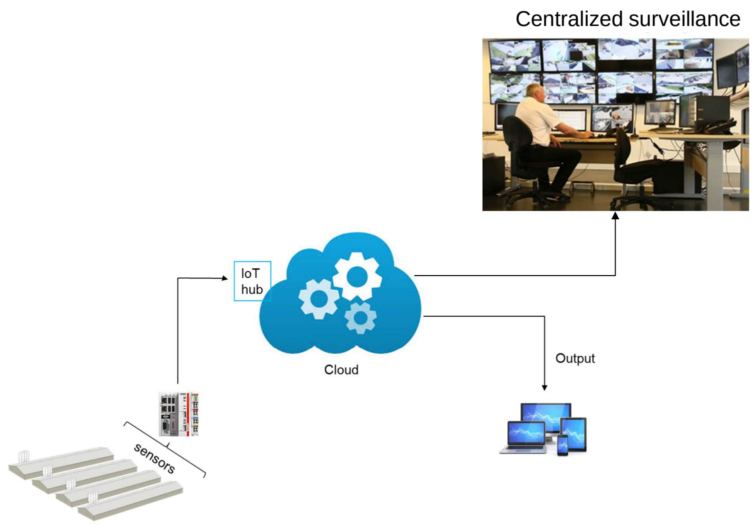
IoT – Farm monitoring, OEM



5

IQinAbox

Central alarm facilitation



6

2.2.2 Ambitions for machine vision

Presentation by Dan Børge Jensen

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The ideas

- Live weight estimation of slaughter pigs
  - Whole pen
  - Single pigs
  - Using interpolated data
- Location-specific counting of slaughter pigs
- Detection of undesired behavior
  (e.g. tail biting)
- Recognition of individual pigs

The basics of Convolutional Neural Networks

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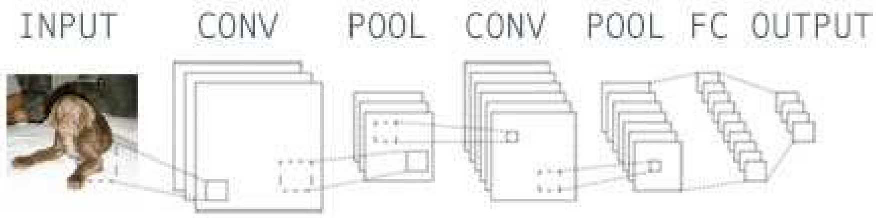
The basics of Convolutional Neural Networks (CNN)



Input:
2D (greyscale)
3D (colour)

Convolution:
Matching multiple small patterns to all areas of the image

Pooling:
Dimensionality reduction

Fully connected:
1D vector

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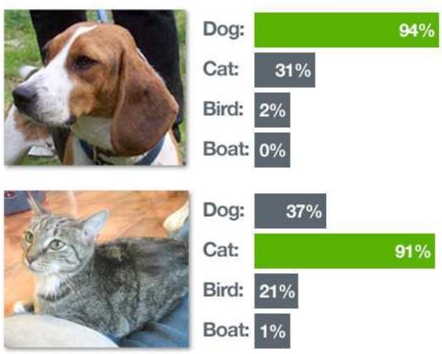
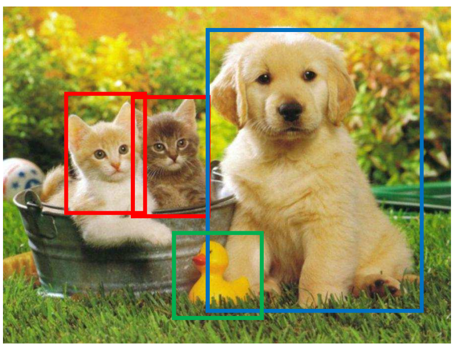
The basics of Convolutional Neural Networks (CNN)

Object Classification

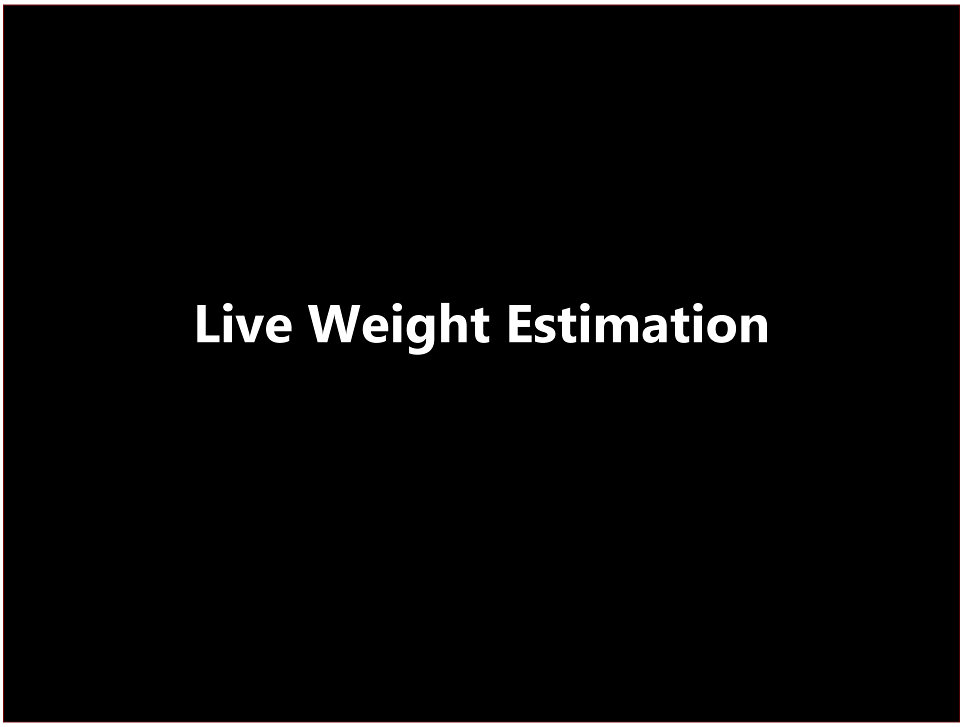


Numerical instead of categorical output
→ ***"image regression"***

Object Detection



Cat **Duck** **Dog**


Live Weight Estimation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Weight estimation – single pig level
(“image regression”)
28.8
kg
56.0
kg
79.4
kg
RMSRE = 4.4 kg

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Weight estimation – single pig level
(object detection + "image regression")

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Weight estimation – Pen level
("image regression")

Mean = 66, SD = 3.5

Mean = 108, SD = 7.0

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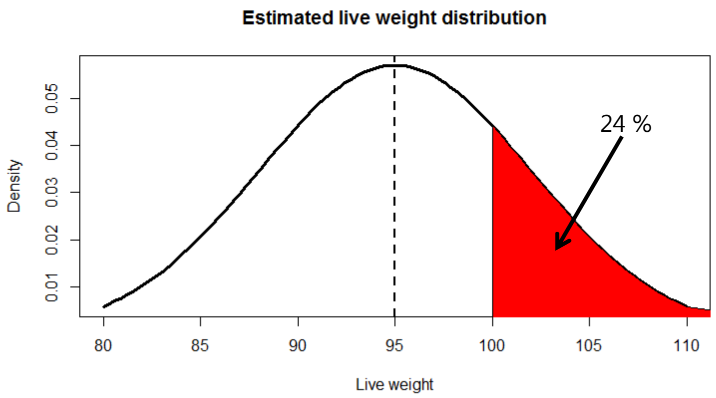
Weight estimation – pen level ("image regression")



Hypothetical:
20 pigs, Mean = 95 kg, SD = 7 kg
Slaughter weight: 100 kg

No. of ready pigs:
0.24 * 20 pigs = 4 pigs

Place-specific Counting of Pigs

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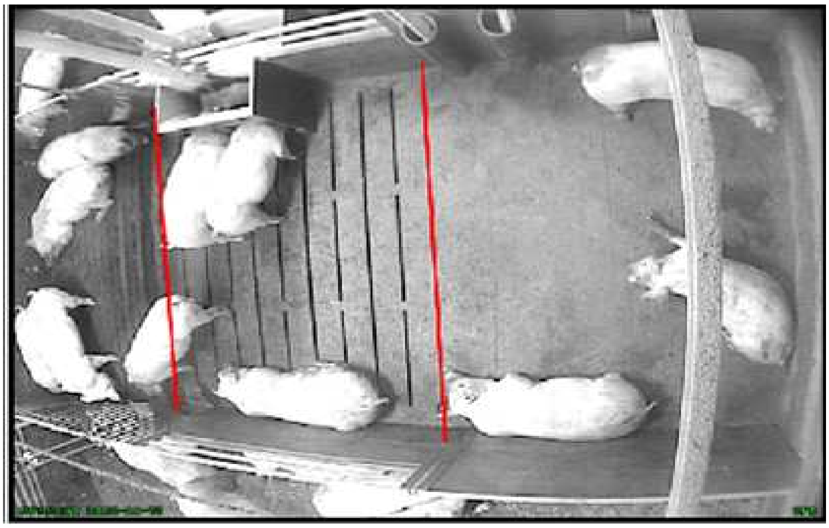
Place-specific Counting (image regression)



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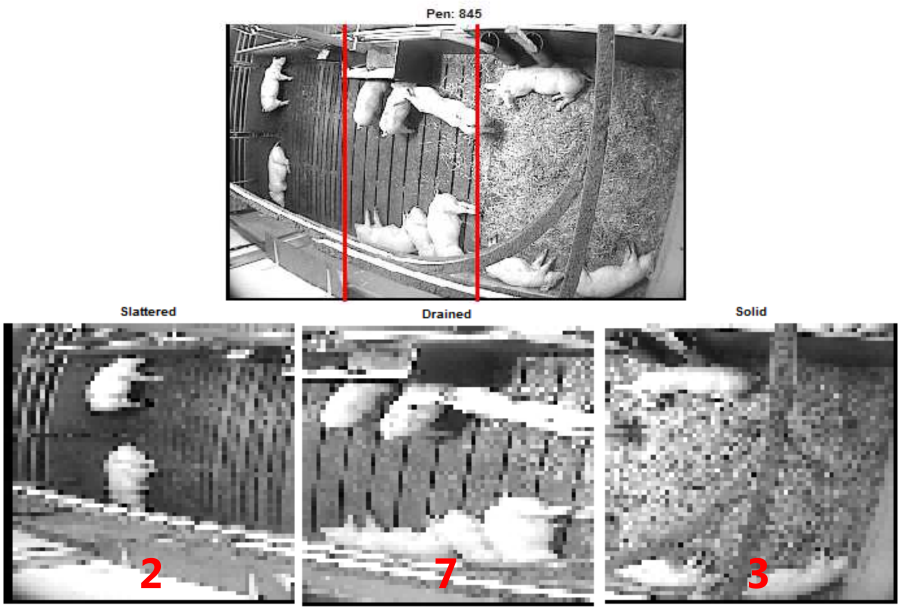
Place-specific Counting (image regression)



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Preliminary results

Training set: Pen 826, N = 3276
Test set: Pen 842, N = 1794

Area	MAE	Accuracy (+/- 1)	95 % C.I. (+/- 1)
Solid	1.43	0.57	0.53-0.61
drain	1.11	0.70	0.66-0.74
spalte	0.54	0.94	0.92-0.96
all	1.03	0.74	0.72-0.76

Automatic Detection of Biting Behaviour

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Detecting Biting Behaviour – object detection

Ear biting **Belly nosing** **Tail sniffing**

Acknowlegdement:
Joanna Klaaborg
(the “Lange Haler” project by UCPH and SEGES)

Conclusions

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Main conclusions

We have the data

We have the ideas
(although we can always use more!)

We have the funding

→ Let's go!

Chapter 3

Publications of the project

The chapter is organized according to publication type, and within type it is, where relevant, organized with the following subsections:

Published or accepted: Articles that are already published or accepted.

Submitted: Articles that have been submitted.

Manuscripts: Articles that will be submitted in the near future (3-4 months) and where a manuscript is currently available.

Furthermore, an appendix presents a list of planned publications.

3.1 PhD theses

The theses of the project are listed in chronological order.

- Jensen, D.B. 2016. *Automatic learning and pattern recognition using sensor data in livestock farming.* PhD thesis submitted to University of Copenhagen, February 2016.

- Pourmoayed, R. 2016. *Optimization methods in a stochastic production environment.* PhD thesis submitted to Aarhus University, March 2016.

- Dominiak, K.N. 2017. *Spatial modeling of drinking patterns as a tool for reducing alarms in pig production.* PhD thesis submitted to University of Copenhagen, August 2017.

3.2 Journal articles

The articles are listed in chronological order. Only articles for international journals with peer review are included in this section.

3.2.1 Published or accepted articles

- Jensen, D.B., N. Toft & C. Cornou. 2014. The effect of wind shielding and pen position on the average daily weight gain and feed conversion rate of grower/finisher pigs. *Livestock Science 167*, 353-361.

- Kristensen, A.R. 2015. From biological models to economic optimization. *Preventive Veterinary Medicine 118*, 226-237.

- Pourmoayed. R., L.R. Nielsen & A.R. Kristensen. 2016. A hierarchical Markov decision process modeling feeding and marketing decisions of growing pigs. *European Journal of Operational Research 250*, 925-938.

- Jensen, D.B. & A.R. Kristensen. 2016. Temperature as a predictor of fouling and diarrhea in slaughter pigs. *Livestock Science 183*, 1-3.

- Larsen, M.L.V., H.M.-L. Andersen & L.J. Pedersen. 2016. Can tail damage outbreaks in the pig be predicted by behavioural change? *The Veterinary Journal 209*, 50-56.

- Stygar, A.H. & A.R. Kristensen. 2016. Monitoring growth in finishers by weighing selected groups of pigs - a dynamic approach. *Journal of Animal Science 94*, 1255-1266.

- Andersen, H.M.L., E. Jørgensen & L.J. Pedersen. 2016. Using Evolutionary Operation technique to evaluate different management initiatives at herd level. *Livestock Science 187*, 109-113.

- Jensen, D.B., H. Hogeveen & A. de Vries. 2016. Bayesian integration of sensor information and a dynamic linear model for prediction of dairy cow mastitis. *Journal of Dairy Science*. *Journal of Dairy Science 99*, 7344-7361.

- Dominiak, K.N. & A.R. Kristensen. 2017. Prioritizing Alarms from Sensor-based Detection Models in Livestock Production - a review on model performance and alarm reducing methods. *Computers and Electronics in Agriculture 133*, 46-67.

- Jensen, D.B., N. Toft & A.R. Kristensen. 2017. A multivariate dynamic linear model for early warnings of diarrhea and pen fouling in slaughter pigs. *Computers and Electronics in Agriculture 135*, 51-62.

- Lopes Antunes, A.C., D. B. Jensen, T. Halasa & N. Toft. 2017. A simulation study to evaluate the performance of five statistical monitoring methods when applied to different time-series components in the context of control programs for endemic diseases. *PloS One 12*, e0173099.

- Larsen, M.L.V., M. Bertelsen & L.J. Pedersen. 2017. Review: Factors affecting fouling in conventional pens for slaughter pigs. *Animal 12*, 322-328.

- Stygar, A.H., K. Dolecheck & A. R. Kristensen. 2018. A new view on body weight in pigs for frequent monitoring. *Animal 12*, 295-302.
- Denwood, M.J., J.L. Kleen, D.B. Jensen & N.N. Jonsson. 2018. Describing temporal variation in reticuloruminal pH using continuous monitoring data. *Journal of Dairy Science 101*, 233-245.
- Stygar, A.H. & A.R. Kristensen. Detecting abnormalities in pigs growth - a dynamic linear model with diurnal growth pattern for identified and unidentified pigs. *Computers and Electronics in Agriculture 155*, 180-189.
- Dominiak, K.N., L.J. Pedersen & A.R. Kristensen. 2018. Spatial modeling of pigs' drinking patterns as an alarm reducing method. I. Developing a multivariate dynamic linear model. *Computers and Electronics in Agriculture*. In press.
- Dominiak, K.N., J. Hindsborg, L.J. Pedersen & A.R. Kristensen. 2018. Spatial modeling of pigs' drinking patterns as an alarm reducing method. II. Application of a multivariate dynamic linear model. *Computers and Electronics in Agriculture*. In press.
- Jonsson, N.N., J.L. Kleen, R.J. Wallace, I. Andonovice, C. Michiee, M. Farish, M. Mitchell, C. Duthie, D.B. Jensen & M.J. Denwood. Evaluation of reticuloruminal pH measurements from individual cattle: sampling strategies for the assessment of herd status. *The Veterinary Journal*. In press.

3.2.2 Submitted articles

- Pourmoayed. R. & L.R. Nielsen. An approximate dynamic programming approach for sequential pig marketing decisions at herd level. Submitted to *European Journal of Operational Research*.
- Mateo, J., D. Florensa, A. Pagès-Bernaus, L.M. Plà, F. Solsona & A.R. Kristensen. A cloud-based decision support system to support decisions in sow farms. Submitted to *Computers and Electronics in Agriculture*.
- Pourmoayed. R. & L.R. Nielsen. A hierarchical Markov decision process for optimizing pig marketing decisions under price fluctuations. Submitted to *Annals of Operations Research*.
- Rojo-Gimeno, C., M. van der Voort, J.K. Niemi, L. Lauwers, A.R. Kristensen & E. Wauters. Assessment of the value of information of precision livestock farming: A conceptual framework. Submitted to *NJAS - Wageningen Journal of Life Sciences*.
- Jensen, D.B., K.N. Dominiak & L.J. Pedersen. Application of convolutional neural networks for automatic estimation of individual slaughter pig live weight. Submitted to *Annals of Operation Research*.

3.2.3 Manuscripts

- Lopes Antunes A.C. & D.B. Jensen. Comparison of time series methods for monitoring temporal trends of Porcine Reproductive and Respiratory Syndrome in Danish swine herds based on serology diagnostic data. To be submitted to *Preventive Veterinary Medicine*.

- Tu, G.J. & H. Karstoft. Image segmentation method for elimination of shadows. Manuscript in Progress.

- Tu, G.J. & Jørgensen, E. Weight estimation of growing pigs in slaughter pens using computer vision. Manuscript in Progress.

- Jensen, D.B. & A.R. Kristensen. Temperature-based detection of diarrhea in slaughter pigs via logistic regression, artificial neural networks, and support vector machines.

- Hindsborg, J. & A.R. Kristensen. From data to decision - implementation of a sow replacement models.

- Hauschild, L., A.R. Kristensen, I. Andretta, A. Remus, L.S. Sousa & C. Pomar. Towards better estimation of real-time individual amino acid requirements of growing-finishing pigs with deviation from its normal feeding pattern.

- Bertelsen, M., L.J. Pedersen & M.L.V. Larsen. Changes in lying location of pigs prior to pen fouling. Ready.

- Jensen, D.B., M.L.V. Pedersen & L.J. Pedersen. Predicting slaughter pig pen fouling from pig position and activity. To be submitted to *Livestock Science*.

3.3 Book chapters with peer review

- Nielsen, L.R. & A.R. Kristensen. 2015. Markov Decision Processes to Model Livestock Systems. In: Plà-Aragonés, L.M. (Ed.): *Handbook of Operations Research in Agriculture and the Agri-Food Industry*. International Series in Operations Research & Management Science. Volume 224, Chapter 19, 419-454. Springer, New York.

3.4 Conference articles with peer review

- Andersen, H.M-L., E. Jørgensen, L.J. Pedersen & L. Foldager. 2015. Can use of online measurements in EVOP designs reduce the time to locate production optimum? *EC-PLF conference in Milan*, 15-18 September 2015.

- Jensen, D.B., C. Cornou, N. Toft & A.R. Kristensen. 2015. A multi-dimensional dynamic linear model for monitoring slaughter pig production. *EC-PLF conference in Milan*, 15-18 September 2015.

- Lopes Antunes, A.C., D.B. Jensen, T. Halasa & N. Toft. 2016. Dynamic generalized linear models for monitoring endemic diseases: moving beyond univariate process monitoring control algorithms. *Annual Conference of The Society for Veterinary Epidemiology and Preventive Medicine (SVEPM)*, 16th-18th March 2016, Helsingør, Denmark.

- Dominiak, K.N., J. Hindsborg, L.J. Pedersen & A.R. Kristensen. 2017. Reducing alarms and prioritising interventions in pig production by simultaneous monitoring of water consumption in multiple pens. *EC-PLF conference in Nantes*, 12-14 September 2017.

- Lopes Antunes, A.C., D. Jensen, T. Halasa & N. Toft. 2017. What tools are useful for monitoring endemic diseases? A simulation study based on different time-series components. *Proceedings of the 3rd International Conference on Animal Health Surveillance*, Rotorua, New Zealand, 2017. p. 5-7.

- Jensen, D.B., K.N. Dominiak & L.J. Pedersen. 2018. Automatic estimation of slaughter pig live weight using convolutional neural networks. *II International Conference on Agro BigData and Decision Support Systems in Agriculture*. Lleida, Spain, 12-14 July 2018.

- Dominiak, K.N., J. Hindsborg, L.J. Pedersen & A.R. Kristensen. 2018. Area-specific predictions of unwanted events using multivariate modeling of water data. *II International Conference on Agro BigData and Decision Support Systems in Agriculture*. Lleida, Spain, 12-14 July 2018.

3.5 Articles in proceedings

- Kristensen, A.R. & D.B. Jensen. 2015. The intelligent pig barn. *International conference on pig welfare: Improving Pig Welfare - what are the ways forward?* Copenhage, 29-30 April 2015. p. 34-37.

3.6 Master's theses

- Xu, Hao. 2017. *Analyses of body weight in growing pigs. The influence of different penetration rates of electronic ear tags for frequent monitoring.* Department of Veterinary and Animal Sciences, University of Copenhagen.

3.7 Oral presentations

- Pourmoayed, R., & L.R. Nielsen. 2013, A Markov model for optimal slaughter pig marketing - An outline of the PigIT project (an example and extensions). *NorForsk Workshop*. Aarhus, Denmark, 13-14 May 2013.

- Pourmoayed, R., L.R. Nielsen & A.R. Kristensen. 2014. A hierarchical Markov decision process modelling feeding and marketing decisions of growing pigs. *Conference of the International Federation of Operational Research Societies* (IFORS). Barcelona, Spain, 13-18 July 2014.

- Pourmoayed, R., L.R. Nielsen & A.R. Kristensen. 2014. A hierarchical Markov decision process modelling feeding and marketing decisions of growing pigs. *Workshop on OR in Agriculture and Forest Management*. Lleida, Spain, 20-23 July 2014.

- Jensen, D.B., N. Toft, A.R. Kristensen & C. Cornou. 2014. Dynamic monitoring of weight data at the pen vs at the individual level. Book of Abstracts of the *65th Annual Meeting of the European Federation of Animal Science*. Copenhagen, Denmark, 25 - 29 August 2014. p224.

- Dominiak, K.N. 2015. Prioritization of alarms from automatic monitoring systems in livestock production - a review. Book of presentations of the *2nd CPH Pig seminar* January 28, 2015 - Up to Date with Pig Research. Copenhagen, Denmark, 28 January 2015. p59.

- Jensen, D.B., 2015 Multivariate Dynamic Linear Models for Monitoring of Grower/Finisher Pigs. Book of presentations of the *2nd CPH Pig seminar* January 28, 2015 - Up to Date with Pig Research. Copenhagen, Denmark, 28 January 2015. p55.

- Jensen, D.B. 2015. Temperature as a predictor of fouling and diarrhea in slaughter pigs. *PhD day, Faculty of Health and Medical Sciences, University of Copenhagen*, 21 May 2015.

- Jensen, D.B. & A. De Vries. 2015. Bayesian prediction of mastitis using sensor data routinely collected in dairy herds. Book of abstracts of the *66th Annual Meeting of the European Federation of Animal Science*. Warsaw, Poland. p297.

- Dominiak, K.N. 2015. How Performance Impairs Implementation - A Review of the Performance of Sensor-based Automatic Monitoring Systems in Livestock Production. Book of abstracts of the *66th Annual Meeting of the European Federation of Animal Science*. Warsaw, Poland. p297.

- Stygar, A.H & A.R. Kristensen. 2015. Evaluation of manual weight measurement system in fattening pigs - dynamic monitoring approach. Book of

abstracts of the *66th Annual Meeting of the European Federation of Animal Science*. Warsaw, Poland. p298.

- Andersen, H.M-L., E. Jørgensen, L.J. Pedersen & L. Foldager. 2015. Can use of online measurements in EVOP designs reduce the time to locate production optimum? *EC-PLF conference in Milan*, 15-18 September 2015.

- Jensen, D.B., C. Cornou, N. Toft & A.R. Kristensen. 2015. A multi-dimensional dynamic linear model for monitoring slaughter pig production. *EC-PLF conference in Milan*, 15-18 September 2015.

- Pourmoayed, R. & L.R. Nielsen. A hierarchical Markov decision process for finding the best replacement policy of fattening pigs. *INFORMS Annual Meeting*, Philadelphia 1.-4. November 2015.

- Stygar, A.H. & A.R. Kristensen. What we can learn from weighing selected group of animals? - A dynamic production monitoring in pig fattening herd. *Maataloustieteen Päivät 2016*, Helsinki 12.-13.1.2016.

- Jensen, D.B. A multivariate dynamic linear model for early warnings of diarrhea and pen fouling in slaughter pigs. Book of presentations of the *3rd CPH Pig seminar* February 3rd, 2016 - Up to Date with Pig Research. Copenhagen, Denmark.

- Lopes Antunes, A.C., D.B. Jensen, T. Halasa & N. Toft. 2016. Monitoring PRRS using laboratory data. Book of presentations of the *3rd CPH Pig seminar* February 3rd, 2016 - Up to Date with Pig Research. Copenhagen, Denmark.

- Stygar, A. H. 2016. Monitoring growth in finishers by weighing selected groups of pigs. Book of presentations of the *3rd CPH Pig seminar* February 3rd, 2016 - Up to Date with Pig Research. Copenhagen, Denmark, 28 January 2015. P23.

- Jensen, D.B., A.R. Kristensen & N. Toft. 2016. Early warning of diarrhea and pen fouling in growing pigs using sensor-based monitoring. Accepted for the *International Pig Veterinary Society Congress (IPVS)*. 07-10 June 2016. Dublin, Ireland.

- Stygar, A.H., K. Dolecheck & A.R. Kristensen. 2016. A new view on the growth of pigs in relation to frequent body weight monitoring. *Joint Annual Meeting (JAM)*. Salt Lake City, Utah, July 19-23.

- Jensen, D.B. & A.R. Kristensen. 2016. Comparison of strategies for combining dynamic linear models with artificial neural networks for detecting diarrhea in slaughter pigs. *Joint Annual Meeting (JAM)*. Salt Lake City, Utah, July 19-23.

- Dominiak, K.N., L.J. Pedersen & A.R. Kristensen. 2016. Simultaneous monitoring of water consumption in eight double pens as a tool for improving welfare and predicting diseases and unwanted behavioral changes in finisher pigs. *Joint Annual Meeting (JAM)*. Salt Lake City, Utah, July 19-23.

- Boel, M. & L. Foldager. Development of a predictive algorithm for a pig farming decision support system. *39. Symposium i Anvendt Statistik*, 23-24 January 2017, Odense.

- Jensen, D.B. 2017. Combining a multivariate dynamic linear model with artificial neural networks for detecting diarrhea in slaughter pigs. Book of presentations of the *4th CPH Pig seminar* February 1, 2017. P52.

- Dominiak, K.N., J. Hindsborg, L.J. Pedersen & A.R. Kristensen. 2017. Reducing alarms and prioritising interventions in pig production by simultaneous monitoring of water consumption in multiple pens. *EC-PLF conference in Nantes*, 12-14 September 2017.

- Jensen, D.B. 2018. Automatic estimation of weaner live weight using artificial neural networks. *5th CPH Pig seminar* January 30, 2018.

- Dominiak, K.N. 2018. Management support by drinking pattern modeling. *5th CPH Pig seminar* January 30, 2018.

- Hauschild, L., A.R. Kristensen, I. Andretta & C. Pomar. 2018. Dynamic feeding intake monitoring in growing-finishing pigs reared under precision feeding strategies. *Precision Livestock Researchers Workshop Seminar*, 3-4 May 2018, Wageningen, The Netherlands.

- Dominiak, K.N. & A.R. Kristensen. 2018. Predicting tail bites and diarrhea amongst growing pigs from changes in drinking patterns - a validation of a dynamic spatial detection system on data from an independent herd. *Precision Livestock Researchers Workshop Seminar*, 3-4 May 2018, Wageningen, The Netherlands.

- Jensen, D.B., K.N. Dominiak & L.J. Pedersen. 2018. Automatic estimation of slaughter pig live weight using convolutional neural networks. *II International Conference on Agro BigData and Decision Support Systems in Agriculture*. Lleida, Spain, 12-14 July 2018.

- Dominiak, K.N., J. Hindsborg, L.J. Pedersen & A.R. Kristensen. 2018. Area-specific predictions of unwanted events using multivariate modeling of water data. *II International Conference on Agro BigData and Decision Support Systems in Agriculture*. Lleida, Spain, 12-14 July 2018.

- Stygar, A.H. & A.R. Kristensen. 2018. Monitoring growth of identified and unidentified pigs using data from an automatic weighing system. Book of

Abstracts of the *69th Annual Meeting of the European Federation of Animal Science*, 27-31 August, Dubrovnik, Croatia. p530.

- Hindsborg, J. & A.R. Kristensen. 2018. From raw data to optimal sow replacement decisions - an integrated solution. Book of Abstracts of the *69th Annual Meeting of the European Federation of Animal Science*, 27-31 August, Dubrovnik, Croatia. p531.
- Jensen, D.B., K.N. Dominiak & L.J. Pedersen. 2018. Automatic estimation of slaughter pig live weight using convolutional neural networks. Book of Abstracts of the *69th Annual Meeting of the European Federation of Animal Science*, 27-31 August, Dubrovnik, Croatia. p437.
- Kristensen, A.R. 2018. The ideas behind the PigIT project. *Closing Conference of the PigIT project*, 13 November, Copenhagen, Denmark.
- Stygar, A.H. 2018. A dynamic approach to monitoring of growth in finishers. *Closing Conference of the PigIT project*, 13 November, Copenhagen, Denmark.
- Jensen, D.B. 2018. Automatic learning and pattern recognition using sensor data. *Closing Conference of the PigIT project*, 13 November, Copenhagen, Denmark.
- Dominiak, K.N. 2018. Spatial modeling of drinking patterns as a tool for reducing alarms in pig production. *Closing Conference of the PigIT project*, 13 November, Copenhagen, Denmark.
- Pedersen, L.J. 2018. Behavioral changes preceding tail biting and pen fouling in slaughter pig pens. *Closing Conference of the PigIT project*, 13 November, Copenhagen, Denmark.
- Domun, Y. 2018. Using machine learning to predict tail-biting, fouling and diarrhea in pigs. *Closing Conference of the PigIT project*, 13 November, Copenhagen, Denmark.
- Pourmoayed, R. 2018. Models and methods for optimization of pig production in a stochastic environment. *Closing Conference of the PigIT project*, 13 November, Copenhagen, Denmark.
- Hindsborg, J. 2018. From raw data to optimal sow replacement decisions - an integrated solution. *Closing Conference of the PigIT project*, 13 November, Copenhagen, Denmark.
- Madsen, T.N. 2018. The IQinAbox project. *Closing Conference of the PigIT project*, 13 November, Copenhagen, Denmark.
- Jensen, D.B. 2018. Ambitions for machine vision. *Closing Conference of the PigIT project*, 13 November, Copenhagen, Denmark.

3.8 Posters

- Andersen, H.M-L., E. Jørgensen & L.J. Pedersen. 2014. Use of evolutionary operation technique on farm level. Proceedings of the *48th Congress of the International Society for Applied Animal Ethology*. Vitoria-Gasteiz, Spain, 29 July - 2 August 2014. p164.

- Pourmoayed. R., L.R. Nielsen & A.R. Kristensen. 2014. A Markov model for optimal feeding and marketing decisions in production units of growing pigs. Book of Abstracts of the *65th Annual Meeting of the European Federation of Animal Science*. Copenhagen, Denmark, 25 - 29 August 2014. p451.

- Jensen, D.B., N. Toft & C. Cornou. 2014. The effect of wind shielding and pen position on growth rate and efficiency in grower/finisher pigs. Book of Abstracts of the 65th Annual Meeting of the European Federation of Animal Science. Copenhagen, Denmark, 25 - 29 August 2014. p451

- Tu, G.J. & E. Jørgensen. 2014. Pig video tracking methods: a review and new trends. Book of Abstracts of the 65th Annual Meeting of the European Federation of Animal Science. Copenhagen, Denmark, 25 - 29 August 2014. p450.

- Jensen, D.B. 2015. Temperature as a predictor of fouling and diarrhea in slaughter pigs. *PhD day, Faculty of Health and Medical Sciences, University of Copenhagen*, 21 May 2015. Programme & Abstracts, p20.

- Jensen, D.B., N. Toft & A.R. Kristensen. 2015. Temperature as a predictor of fouling and diarrhea in slaughter pigs. Book of abstracts of the *66th Annual Meeting of the European Federation of Animal Science*. Warsaw, Poland. p303.

- Jensen, D.B., A. De Vries. 2016. Combining a multivariate dynamic linear model and a naive Bayesian classifier for mastitis detection. Book of abstracts of the conference on *Precision Dairy Farming (PDF)*. 21-23 June 2016. Leeuwarden, The Netherlands.

- Lopes Antunes, A.C., D.B. Jensen, T. Halasa & N. Toft. 2016. What to look for when monitoring animal diseases? *Annual Conference of The Society for Veterinary Epidemiology and Preventive Medicine (SVEPM)*. 16-18 March 2016. Helsingør, Denmark.

- Denwood, M.J., D.B. Jensen, J.L. Kleen & N.N. Jonsson. 2018. Association between temporal patterns in continuously monitored reticuloruminal pH data and production characteristics in dairy cows. *15th International Symposium of Veterinary Epidemiology and Economics*. 12-16 November 2018, Chang Mai, Thailand.

3.9 Articles in magazines

- Pourmoayed, R. & L.R. Nielsen. 2016. Culling pigs under price fluctuations. *ORbit 27*. The Danish Operations Research Society.

3.10 Interviews

- Lindgaard, T.K. 2012. Nu rykker it udstyret helt ind i stierne. *Hyologisk* April 26th 2012.

Appendix A

Planned articles

The following list presents articles planned by the first author.

- Jensen, D.B., K.N. Dominiak & L.J. Pedersen. Pilot study: Automatic estimation of slaughter pig live weight using convolutional neural networks.
- Nielsen, P.P. et al. Automatic detection of competition around drinker in fattening pigs using video recordings. To be submitted to *Computer and Electronics in Agriculture*.
- Nielsen, P.P. et al. Early detection of diarrhea in fattening pigs by means of activity and competition around the drinker. To be submitted to *Animal*.
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