
Designing the optimal robotic milking barn

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The PhD project was intended to make a three-way contribution:

- 1) To the development of a science-based methodology for designing the layout of the robotic milking barn (RMB), taking into account the many factors that directly influence the layout design, such as existing physical layout of the barn, cow behaviour, management practices, potential capacity and actual utilisation, and feeding routine.
- 2) To translate the methodology into a practical design tool, embedded in a user-friendly software application, ready for use in the farmer's home during a consultation;
- 3) To set up examples that demonstrate the proposed methodology, show a way through the complexity of finding an optimal solution, and indicate how a solution may be generalized to other cases. This PhD study has been completed and published by IMAG and Wageningen University; no further research on the same issue is necessary - the onus is now on the industry to implement this proposed design methodology on a daily basis.

Nowadays, the number of dairy farms has decreased while the remaining farms have grown in size and have modernized, often by purchasing a milking robot. These robots affect farm labor, cow productivity, animal welfare, feeding routines, building construction and management practices. All these aspects need to be taken into consideration when designing the layout of a robotic milking barn (RMB).

Summary

Introduction

The traditional barn has a milking parlor oriented design and should be redesigned according to the robotic milking concept when a milking robot is to be integrated. The actual capacity (performance) of a robot depends on access of the cow to the robot. The entire system (barn design, its layout, feeding and cow-traffic routines, management practices) should encourage 'voluntary milking', i.e. it should ensure sufficiently frequent visits of the cows to the robot. Facility (or space) allocation is an important consideration and it determines system layout; an optimal layout balances adequate facility capacity against over capacity. It should balance animal welfare on the one hand and facility utilization on the other. So, the two conflicting requirements (to be optimized) are the economical need for high facility utilization and animal welfare and these two should be incorporated into the management practices and physical layout. However, the actual capacity of each facility (such as robot, forage lane, concentrate feeder) in the RMB depends on its accessibility to the cow (animal behavior). There is also wide diversity among farmers and local conditions, therefore, the optimal layout may vary among farms. In addition, milking robots are relatively new, there are only few precedents and little experience to draw upon when designing robotic milking barns. Therefore there is clearly a need for a design methodology for RMBs that is based on scientific rules (as opposed to subjective experience), animal behavior and welfare, interactions among cows, facilities and management practices, and parameters that are adjustable to every farmer or site. Thus, creating an RMB layout is a multidisciplinary field, requiring an interdisciplinary approach.

The newly developed methodology has been implemented into a practical design tool (a software application) intended for research as well as practical application that can be used daily by engineers, researchers, advisors and robot manufacturers. *The objective* of this study was to develop a design methodology for determining the optimal layout for a robotic milking barn before the barn is built. The optimal RMB layout (the solution) has to be adjusted for individual farm conditions, unique to any farmer or site, but the design methodology should be universally applicable.

Materials and Methods

Experimental investigation

Four experiments were conducted, two under research conditions and two in commercial farms. In the first experiment, we gave the animal freedom of choice and assumed that its activities would not be such as to impair its own welfare. This experiment aimed to explore the stochastic nature of the facility utilization in a robotic milking barn - independent of the barn layout. To minimize restrictions on the cows' access to the facilities, the barn contained less than half the number of cows for which it was designed, to ensure maximum availability of facilities (over allocated capacity) and the cows were fed continuously round the clock. The activity of each cow in the group was monitored on an individual basis. The intensity and sequence of use of the facilities and cow behavior was studied and statistically quantified. It results in a tremendous database for instance, recording 10 cows for two weeks provides around 36 000 events (milking,

eating, lying, etc), each one including variety of information (entering and exit time, milk yield, food consumption and so on). Consequently, the first engineering/mathematical challenge was to develop an efficient data processing algorithm and software application capable for handling such a huge database.

In the second experiment, forage food was given twice a day, and the number of cows in the group was increased to the maximum capacity of that barn. This experiment aimed to validate the model under conditions that were different from those for which that the model was developed (mainly different layout, feeding routine and number of cows). Groups of 10, 20 and 30 cows were kept in a loose housing system with cubicles originally designed for 30 cows. Each group was monitored for 3-4 weeks (excluding the start-up periods). The third and fourth experiments were conducted in two commercial barns in farms typical of those to be found in the Netherlands. These experiments aimed to validate the model under commercial conditions and with a different type of robot. In the first farm the robot had been installed in an existing barn after refitting. In the second farm an entirely new barn had been designed specially for robotic milking, with the aim of installing more than one robot (in the near future). During the 4-5 week experiment period, each farm had milked around 60 cows by using a single robot. The forage food was distributed in the morning by a mixing wagon and whatever remained in the evening was pushed toward the cows. The four experiments are described in detail by Halachmi (1999).

A closed queuing network model, a mathematical representation of a robotic milking barn was developed (Halachmi *et al.*, 2000a). We use an approximate mean-value algorithm to evaluate important performance criteria such as the number of waiting cows, their waiting time and the utilization of the facilities in the barn. The model incorporated farmer 'aspiration levels', animal welfare in terms of queue length and waiting time; cost in terms of facility utilisation, and visual analysis of the barn performance.

Developing the queuing network model

A behavior-based simulation (BBS) model, which enables a designer to optimize facility allocation in a barn, has been developed (Halachmi 2000) and validated (Halachmi *et al.*, 2001a). The BBS requires fewer simplifying assumptions than the queuing network model. Simulation experiments allow equipment, layouts and management practices to be evaluated in combination. We conducted two types of validation experiments:

- a) observation of cow behavior in real (non-simulated) barns, and
- b) computer simulation.

Developing computer simulation model and validation

The measurements from three real robotic barns were statistically compared with simulation data under a variety of scenarios, including commercial barns. The simulation model appear to be a valid, accurate representation

of the real system under commercially feasible conditions. This hypothesis was tested statistically and was not rejected at $\alpha=2.5\%$. So the conclusion is that the model is a practical design tool, enabling the designer to optimise facility allocation and barn layout.

Metamodel and optimization algorithms

The BBS model was integrated with regression metamodel, full factorial design, and optimization algorithms (Halachmi *et al.*, 2001c). The Metamodel transformation appeared to be a first-order polynomial, so that Kuhn-Tucker conditions are both necessary and sufficient for a global optimum point to be found by ordinary algorithms such as projection methods or Simplex. Since the integration allowed a global optimum to be found, it completed the mathematical development of that integrated design methodology.

Results and discussion

The main finding of the experimental investigation in the RMB facilities were:

- a. The cows' access (arrival time) to any of the RMB facilities and the duration of each visit (service time) can be represented as Exponential, Normal, Weibull, Log-Normal and Beta distributions (Halachmi *et al.*, 2000b).
- b. The robotic barn is actually a closed queuing network, i.e., it contains a series of service facilities (robots, concentrate feeder, forage lane, cubicles, water troughs, etc.), at some or all of which, cows must receive service. After having been serviced in facility *i*, the cow proceeds to facility *j*, i.e., a transition probability matrix which represents the interrelations between facilities utilization (Halachmi *et al.*, 2000a).
- c. From the transition matrix it can be seen that in 90% of the cases, a concentrate feeder visit follows a robot visit. Thus the concentrate feeder (stand-alone or in the robot) is an effective device to force the cows into a particular cow-traffic routine. The transition matrix also indicates that there were many movements between the forage lane and the cubicles and between the forage and water troughs. If a forced routine prevented these movements, it could impair animal welfare and feed intake.
- d. Two peaks during forage feeding times dominated the time pattern of the cows' feeding behavior and influenced the entire system performance.
- e. In our experiments the observed cubicle utilization never exceeded 75%, which suggests that it would be feasible to have fewer cubicles than cows without adversely affecting cow behavior.
- f. Robot utilization in the two commercial RMBs was rather high (about 85% throughout the 24 hours) and its attachment performance met practical requirements (attachment failures occurred in only 1.25% of the visits occupying 1.00% of the robot's time). This suggests that robotic-milking has progressed from its development phase to having sufficient reliability for mass production.

Operational research into facility utilization (Halachmi *et al.*, 2000b) forms the central theme of this thesis: quantifying animal behavior in relation to facility utilization as a continuous-time stochastic process has opened the way for the application of systems engineering and theories (such as: queuing-network models, Markov chain, and computer simulation) to the design of robotic milking barns. The closed queuing network model (Halachmi *et al.*, 2000a) cannot be solved exactly, but the arrival theorem and mean-value analysis produced good approximations (the accuracy was 99.5-99.9% for the facility utilization and 98-99% for the mean waiting time) and by use of the aspiration-level model, RMB design can meet both economic and animal welfare needs. The findings also suggest a possible approach to defining animal welfare “ISO” standards.

The main conclusions of the simulation development and experiments were:

- a. The simulation model appears to be a valid, accurate representation of the real system, under commercially feasible conditions (Halachmi *et al.*, 2001a).
- b. The simulation model and its animation improve communication between barn operators and designers. It allows the farmer to integrate his chosen factors into the model and highlights potential design options before the barn is built. The farmer can gain assurance before building that the proposed design would actually meet his specified requirements and the model tends to be trusted since it looks like a valid representation of the farmer’s barn. Halachmi (2000) presents the user-friendly interface, and its animation.
- c. An initial layout can be fine-tuned to produce a balanced system, a so-called ‘local optimum’ specific for a given farm within a reasonable time on the farmer dining table. A simulation run took only 1½ minutes on a 200 MHz Laptop PC (Halachmi, 2000).

Having been validated, the simulation model becomes a practical design tool for optimising a barn layout. Under the given conditions of two specific farms, the model provided the optimal facility allocations: farm A, 1 robot: 36 forage lane positions, 60 cubicles and 71 cows; and Farm B, 2 robots: 3 water troughs, 103 forage lane positions, 105 cubicles and 132 cows. The optimal layout calculated in the case study is unique for a specific farmer, but the methodology developed in this thesis is universally applicable; the parameters can be adjusted to other farmers, sites or milking robots.

In the past, modelling, systems engineering, operational research and computer simulation have revolutionised the design of complex industrial systems. Likewise, this study may be said to be a contribution to a further revolution, this time in the design of livestock systems. Using the proposed design methodology, a model of a future barn can be created which will help to make effective decisions. Before the barn is actually built, it is

Conclusions

possible to predict how the barn will respond to changes in design or operation and compare what will happen under a variety of scenarios. Among other things it is now possible:

- a. to predict facility utilisation and cow queue length;
- b. to calculate the optimal facility allocation: the necessary numbers of cubicles, forage lane positions, water troughs, concentrate feeders and robots;
- c. to advise the individual farmer on the choice of robot location, cow traffic routine, required floor space in front of each facility (waiting area), feeding routine, separation area and automatic cleanings; and
- d. to gain the assurance before building that the proposed design would actually meet pre-specified requirements.

In general this research has shown that behaviour-based simulation is adjustable for any farmer or site, so there is no necessity for further data acquisition under research conditions.

The research enables us to use the simulation as a practical tool in the dairy business arena. Some examples :

- Evaluating different layout structures based on the farmer's individual preferences or different layout concepts while balancing the whole operation.
- Calculating future needs in cases where the dairy intends to expand the herd size.
- Costs calculations can be done based on various scenarios, taking into account investment needed for the different plan.
- The simulation applies for robotic and non robotic dairies.

The simulation software is ready to be picked-up by a robot manufacturer or a dairy business global player that may purchase the know-how. More information can be accumulated in order to address the full range of practical situations and additional data from more farms may also improve the model validity. Data can be collected by the industry in the course of day-to-day designing and the RMB designs, layouts and operational data can be stored in the public domain (such as an Internet site) accessible to other firms, in accordance with the principles of free dissemination of science. The onus is now on the industry to implement this proposed design methodology on a daily basis.

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