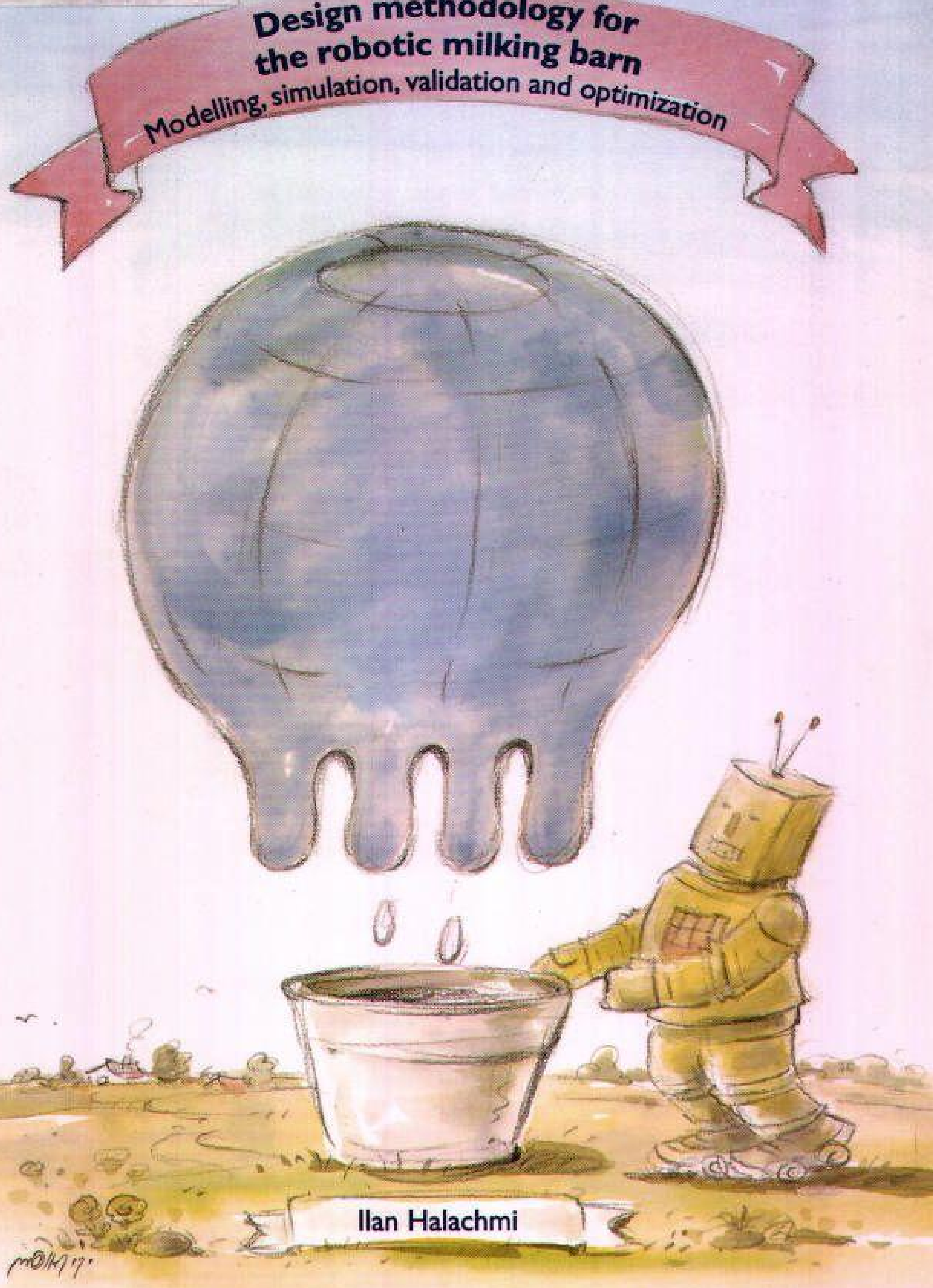
Design methodology for the robotic milking barn

Modelling, simulation, validation and optimization



Ilan Halachmi

Propositions

1. A major criticism of modern intensive farming is that it might impair animal welfare. The design methodology in this thesis could contribute to the development of ISO standards for animal welfare, based on parameters such as cow queue length, and available time windows for access to a facility (this thesis).
2. This research has progressed to a point at which the behaviour-based simulation can be run on a farmer's kitchen table; the onus is now on the industry to implement the proposed design methodology (this thesis).
3. Competition today is not between products, it is between business models (Fortune Magazine, 1999).
4. In a research institution, irrelevance is a bigger risk than inefficiency.
5. "If a hammer is the only tool one has, he might tend to view each problem as a nail". Researchers should not jump into simulation without assessing the feasibility of solving the problem by less costly techniques (O. Balci, 1987).
6. The principal of free dissemination of scientific results is highly relevant for implementing the methodology; barn designs, layouts and operational data should be stored in the public domain – e.g., in an Internet site - and should be accessible to everybody (this thesis).
7. The best way to predict the future is to create it. Each future barn should be created with the aid of simulation.
8. Our inclination to seek regularity and to enforce rules on nature, leads us to dogmatic thinking, or in general, to dogmatic behaviour; we expect regularity everywhere and try to find it even where it does not exist (Karl R. Popper, 'Science: conjectures and refutations').
9. In the Silicon Valley, a six-digit signing bonus is common for a young knowledgeable worker (Wall-Street Journal, 1999). It reduces the possibilities for universities to attract young people, but a real six-digit focused brain is unsuitable for academic research.
10. Models for adults = bazookas for children (Jack P.C. Kleijnen).

Halachmi I., Design Methodology for the Robotic Milking Barn; Modeling, Simulation, Validation, and Optimization. Ph.D. thesis, Wageningen University, 1999

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Modelling, simulation, validation and optimization

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Design methodology for the robotic milking barn

Modelling, simulation, validation and optimization

Ilan Halachmi

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Abstract

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The traditional barn design is a milking parlour oriented. To integrate a milking robot the barn should be redesigned according to the robotic milking concept. The entire system (barn design, feeding and cow-traffic routines, management practices) should encourage 'voluntary milking', i.e., it should ensure sufficiently frequent visits of the cow to the robot.

An optimal layout should balance animal welfare, on the one hand, and the economic need for high facility utilisation, on the other hand. These two conflicting forces (which are to be optimised) should be incorporated into management practices and physical layout. However, the actual capacity (performance) of each facility (such as robot, forage lane, concentrate feeder) in the robotic milking barn (RMB) depends on cow access (animal behaviour), barn design, farm routine and management practices. There is also a wide diversity among farmers and local conditions, therefore the optimal layout may differ among farms. Numerous important factors are evaluated as a system when RMB is designed, but it is usually difficult to quantify how consideration of these factors may affect production or income. Taken together these factors and their variations mean that we are dealing with a quite complex system.

The optimal RMB layout (the solution) has to be matched to individual farm conditions, adjustable for any farmer or site, but the design methodology should be universally applicable. Therefore, *the objective* of this study was to develop a design methodology for finding the optimal layout for a robotic milking barn before the barn is built, and to implement the methodology into a practical design tool, embedded in a user-friendly software application, ready for use in the barn during a consulting session.

Four experiments were conducted, two under research conditions and two in commercial farms. They aimed to explore the stochastic nature of the facility utilisation in a robotic milking barn, and to validate the model under a variety of scenarios.

A closed queuing network model for a robotic milking barn was developed, and a behaviour-based simulation (BBS) model, which enables a designer to optimise facility allocation in a barn, was developed and validated. Having been validated, the simulation model becomes a practical design tool for optimising a barn layout. The design methodology was finalised by integrating the queuing network model, the BBS model, a regression metamodel, full factorial design, and optimisation algorithms.

By using the proposed design methodology, a model of a future barn can be created, which will help to make effective decisions. It is possible to predict how the barn will respond to changes in design or operation, and to compare what will happen under a variety of scenarios. Among other things, it is now possible:

- to predict facility utilisation and cow queue length;
- to calculate the optimal facility allocation: the numbers of robots, cubicles, forage lane positions, water troughs and concentrate feeders that are needed;
- 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, automatic cleaning; and
- to gain assurance before building that the proposed design would actually meet the specified requirements.

In general, this research has reached a stage at which a behaviour-based simulation is adjustable for any farmer or site. The onus is now on the industry to implement this proposed design methodology on a daily basis.

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To Shuli for all her patience, understanding, and love.

And to my parents, Amir, Tal & Willie, Anat, Savta Sara, and Algom

Acknowledgements

Though I had no hypothesis in mind when I began this research; I felt there was something interesting in the phenomenon of voluntary arrival to the milking robot. That led to this thesis about designing the optimal robotic milking barn.

First and foremost, I want to thank my supervisors, Bert Speelman, Aalt Dijkhuizen, Jos Metz and Ephraim Maltz, for their encouraging attitude, sustained through many "tiresome" and long discussions, and their way-outside-the box thinking. Their power of abstraction helped me organize seemingly complex matters. I am especially grateful to Jos Metz for being much more than a professional adviser and for very important day-to-day assistance, well above the call of duty, and to Ephraim Maltz whose friendship and encouragement were crucial in persuading me that PhD research can be fun. Uri Peiper contributed first by convincing us that few years in The Netherlands could by and large be a particular pleasure, and later kept his eye open to ensure that it was a pleasure.

I greatly profited from the unique expertise of Hans Heesterbeek (CBW), Paul van Beek (Wageningen Univ.), Ivo Adan and Jan van der Wal (Eindhoven Univ.) and Jack Keijnen (Tilburg Univ.). Many of the concepts presented in this thesis emerged during lengthy discussions with them, and underwent development through dumping old ideas and coming up with new ones.

Particular thanks are due to Ivo Adan (Eindhoven Univ.) for his tremendous help in queuing network modelling and for very many useful e-mail discussions. And I owe special thanks to Jack Keijnen, for his outstanding expertise in the validation and metamodelling areas. This thesis could not have been finalized in time without his goodwill and his very sportive personality.

Like a cookbook, this thesis presents many recipes that the author has collected over the years. A few of the recipes may be original. Some may be variations of someone else's originals. Many ideas and procedures have been picked up from discussions with colleagues. After the passage of time, one can no longer remember who originated what idea, and after the passage of even more time, it might seem that all of the really good ideas originated with me, a proposition that I know is indefensible. I am indebted to my friends and colleagues who served with me in IMAG-DLO and Wageningen University during the 3 years I served that society. I am also grateful to the Volcani Center (Israel). These are the three organizations from which I have learned the most about scientific working and agricultural engineering.

I would like to express my gratitude to a number of colleagues who have helped me along the path by providing valuable knowledge: Carolien Ketelaar-de Lauwere, Durk Swierstra, and Mark Bracke. I am especially grateful to Rene Braam for help in this as in all things. Also to many others who helped in the data collecting and publication processes. This thesis could not have been written without the field data collected by Frans Ettema and Aart van't Land and the crucial advice of Tal Choen.

My greatest thanks are to my wife Shuli, who made the most essential contribution to this

award: asking periodically whether discrete-event stochastic models were more important than a family or whether optimising a barn was a more applied activity than living the unique life we are given. She kept the work in the right proportion and direction, and without her, this thesis and, in fact, all my current running projects would have gone astray.

I intended to write a thesis worthy of note by researchers and practitioners working in the area of designing robotic dairy barns. I trust you will find the presented concept applicable to your own benefit.

Contents

Introduction

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1. State of the art in robotic milking barn design

We are witnessing a gradual shift in number and size of dairy farms: the number has decreased dramatically while the remaining farms have grown in size and have modernised[1-4]. One of the modernising options is to buy a milking robot, which will reduce the labour force (by 66.1% according to Sonck[5]), improve productivity[6-8] (switching from two to four milkings per day increases milk yield by 15%)[9], and influence cow behaviour[10-12], feeding routine[13], and management practices[14]. All of these effects need to be taken into consideration when designing the optimal layout of a robotic milking barn (RMB).

Designing a layout involves many factors related to nutrition, health and growth, as well as other activities of the dairy operation. Buildings, equipment, facilities, and their relative locations (the layout) are tools that enable essential tasks to be carried out on a regular basis. Flow of animals and materials, future expansion, management and labour requirements, cow traffic, pollution control, and the animal environment are all important considerations in layout design. Creating an environment that meets the needs of the animals being housed is essential; if the basic needs of the animals are not satisfied, no amount of management can guarantee success.

More than one group can be housed in the same barn, each being considered separately for management purposes, with respect to nutrition requirements, medical treatments, sanitation and breeding[15]. Manure management certainly influences barn design; if also affects the overall farm activities: daily hauling, fertiliser use, feeds grown, animal health, and potential for pollution[15]. However, grouping strategy and manure management are only two of the many factors which affect layout design: changing management practices in response to new technology and breeding advances, feed disposal and storage, state or local regulations, acquisition of additional animals and production goals for the next 5 to 10 years, drainage, wind direction, milk truck access, etc. A well designed layout provides: adequate resting and exercise space, adequate feeding space, enough water troughs, a space to group animals by size or age, good quality fresh air, drive-through feeding alleys sized for a feed wagon, clean lots to maintain sanitary conditions, an isolation area for sick animals, provisions for lifting cows unable to stand, access to veterinary treatment, access for removing dead animals, an area from which to observe the animals, a hoof trimming facility, housing for calves and heifers, etc[15].

In order to look at the "big picture" (how components/ systems fit and work together, how the robot fits the dairy housing system, how the robot fits the dairy management system, future expansion), and simultaneously to pay attention to the details (bedding material, comfortable floor, etc) - a co-operative or team approach is needed[16]. A design dilemma is that numerous important factors are evaluated as a system when designing a barn. But, it is usually difficult to quantify how these factors may affect production or income.

Designing an RMB layout involves further complications because a milking robot is an expensive, specialised, complex facility that must work round the clock every day. Its performance (actual capacity) depends on the cows' actual access to the robot, i.e., animal behaviour (assuming that the robot has enough mechanical capacity, attachment and computing capabilities, and reliability). Unlike the milking parlour, the RMB design and management should support the "voluntary milking" concept[10]. Thus, RMB layout design is a multidisciplinary field which demands an interdisciplinary approach. Milking robots allow cows to be milked without human intervention, thereby making more frequent milking feasible, which increases milk production without introducing additional labour. On a farm with a milking parlour, the farmer brings the cows to the milking site, whereas with an RMB the cow is expected to arrive voluntarily round the clock. Parlour-oriented farms have been designed with workers' needs paramount over animals' needs, but with robotic milking, the entire system (barn design, feeding and cow-traffic routines, management practices) must to encourage 'voluntary' visits to the milking robot and, therefore, must focus primarily on the cows. Unlike the milking parlour practices, the robot performance is very sensitive to the farm design and operations. Cow traffic can be free or directed (one-way gates) but design principles such as 'no lying down immediately after milking' should be maintained (in order to reduce mastitis problems), and this mean that the barn layout must be carefully planned. However, because the milking robot represents new technology, there are few precedents and little experience to draw upon. Whereas the design of a traditional (milking parlour oriented) barn is based on extensive experience (many thousands of farms in Western Europe and the USA have been using milking parlours for decades), experience with robotic barns is (relatively) non-existent. There is also a wide diversity among farmers and among local conditions, therefore the optimal layout differs from farm to farm[17,18].

Many researchers have addressed the complex problem of designing the layout of an efficient RMB[7-14, 19-23]. It is not a negligible problem; for example, in 1997 there were 37,000 dairy farms, with 1.67 million dairy cows in the Netherlands; there were 43.3 million dairy cows in the US and 220 million world wide[1-4]. The leaders in the milk production (per cow) 'league' are still Israel, the Netherlands, and North America. However, regional giants like Brazil are emerging into the modern milk-production arena. The last significant improvement in milking techniques (the advent of the milking machine) resulted in all farmers (in the developed countries) switching from milking by hand to mechanical milking[24]. Likewise, milking robots have a huge potential market; if the robot price falls considerably, the same phenomenon may be repeated, with many farmers in the developed countries switching from mechanical milking to robotic milking. This prognosis is supported by the fact that although milking robots came onto the market only a few years ago and are still suffering from 'teething troubles', the two robot manufacturers in the Netherlands are installing more than 200 robots per year[25]. Other companies say they are in the final stages of their robot development[26,27]. Robot prices are therefore likely to fall, because the development costs have been recouped, the 'Dutch monopoly' is about to be broken and new global players are entering the market. Also, prices should fall simply because less "material" is involved in sequential milking for 24 hours per day instead of twice a day in parallel. For example, 120 cows can be milked by two Lely® robots (in total, two stands) but a farmer who builds a parlour will probably build a 16-stand milking parlour with all the accompanying milking equipment, pipe installation, iron construction, concrete stage, etc, that the 16 stands need. In contrast, the robot costs cover just two stands, additional electronics and the two arms. As computing power improves, the latter will become cheaper.

A milking robot is important equipment for a dairy farmer, but a milking system alone does not produce the milk: the cow and operator are equally important. Getting all three components to function harmoniously is the key to an efficient and successful RMB. Furthermore, the major criticism of modern, intensive, animal husbandry systems has been that they impair animal welfare. It would, therefore, seem sensible to design facilities with which farm animals are in harmony; in this way suffering would be reduced and welfare would be assured. The idea of designing an animal facility according to what the animal itself would prefer is not new[28-34] and has been receiving increasing recognition recently. For example, only 270 research papers had appeared in this area during the 1992-3, compared with 990 papers in 1997-8[35]. Many of these papers derive useful rules or equations for supporting the design, but I have not found any paper that has explicitly incorporated the animal behaviour into the engineering design process, and has provided a practical design tool for optimising the entire barn as a balanced system.

During the last 10 years computer simulation (including graphics and animation) has graduated from the laboratories into the public domain. In the last five years the computer animation industry has reached the hundred million dollar mark and is still growing. The burgeoning use of system engineering techniques such as computer simulation has revolutionised the design of manufacturing systems, telephone networks, banks, supermarkets, and more. Simulation avoids the difficulties of real barn experimentation – being flexible and free from unimportant details – as long as the simulations are correctly validated[36-40]. Recent developments in computing power and simulation techniques have increased the modelling power, thus enhancing their potential value in RMB design. Nevertheless, one should not leap into computer simulation (CS) without assessing the feasibility of solving the problem with a simpler technique. Analytical modelling techniques may provide a less costly solution. In the 1980s, analytical models such as queuing networks (QN), Markov chains (MC), and optimisation algorithms appeared to be effective techniques for studying the performance of complex manufacturing systems, including resource allocation and complicated interconnections in a system[41,42]; Nevertheless, these techniques were not used to design complete dairy barns. The investment in a large robotic milking barn (RMB) might approach the cost of a medium-size factory (for example, in the Netherlands an RNB for 120 cows + milk quota and cows usually costs more than three or four million NLG). Until now, however, while the design of a medium-size factory is supported by CS, QN and MC, that of an RMB still relies on traditional methods and rules of thumb.

In brief, there is clearly a need for a design methodology for RMBs that is based on scientific rules, animal behaviour, and interactions among cows, facilities and operators, and that is adjustable to every farmer or site. System engineering techniques may provide the theoretical concepts required to set optimal layouts, and the newly developed methodology should be implemented into a practical design tool (software application) that can be used daily by engineers, researchers, advisors and robot manufacturers. This methodology enables a designer to investigate the interactions among a farmer's management attitude, facilities, layout and cow behaviour before the building is constructed.

2. Problem investigated and aim

Facility (or space) allocation is an important consideration that determines a system layout[43,44]; an optimal design balances adequate facility capacity against over capacity. But the necessary capacity of each facility (such as robot, forage lane, concentrate feeder) in the RMB depends on the amount of cow access, i.e., cow behaviour. So, *the aim* of the present study was to develop a design methodology for finding the optimal layout for a robotic milking barn, a methodology intended for research as well as practical application. This methodology had to take into account animal behaviour, farm routines and management practices, together with the structure of the layout and facility capacities. The optimal RMB layout (the solution) has to be adjusted for each farm, but the design methodology should be universally applicable, adjustable for any farmer or site.

The study was intended to contribute in three ways: 1) to develop a science-based design methodology for the RMB, taking into account the factors that directly influence the design, such as physical layout of the barn, cow behaviour, facility capacity and utilisation, feeding routine and management practices; 2) to implement the methodology as a practical design tool, embedded in a user-friendly software application; 3) to set up examples that demonstrate the proposed methodology, shed light on the complexity of the problem, and provide insight into the procedure for obtaining a solution that may be generalised to other cases.

3. Concept and synopsis

The concept of system engineering and operational research plays an important role in this study, as it may do in the design of future livestock systems, including RMBs. System theory needs to be employed to handle the myriad processes and possible configurations that characterise livestock systems. As already noted, RMB layout design is a multidisciplinary area requiring interdisciplinary knowledge. It involves animal behaviour study together with analytical models and computer simulation. Figure 1 sketches the sequences of the project phases and their links with publications and thesis chapters. It can be seen that quantifying the relationship between animal behaviour and facility usage as a stochastic process opened the way to using system theories (such as QN, MC and CS) for designing robotic milking barns.

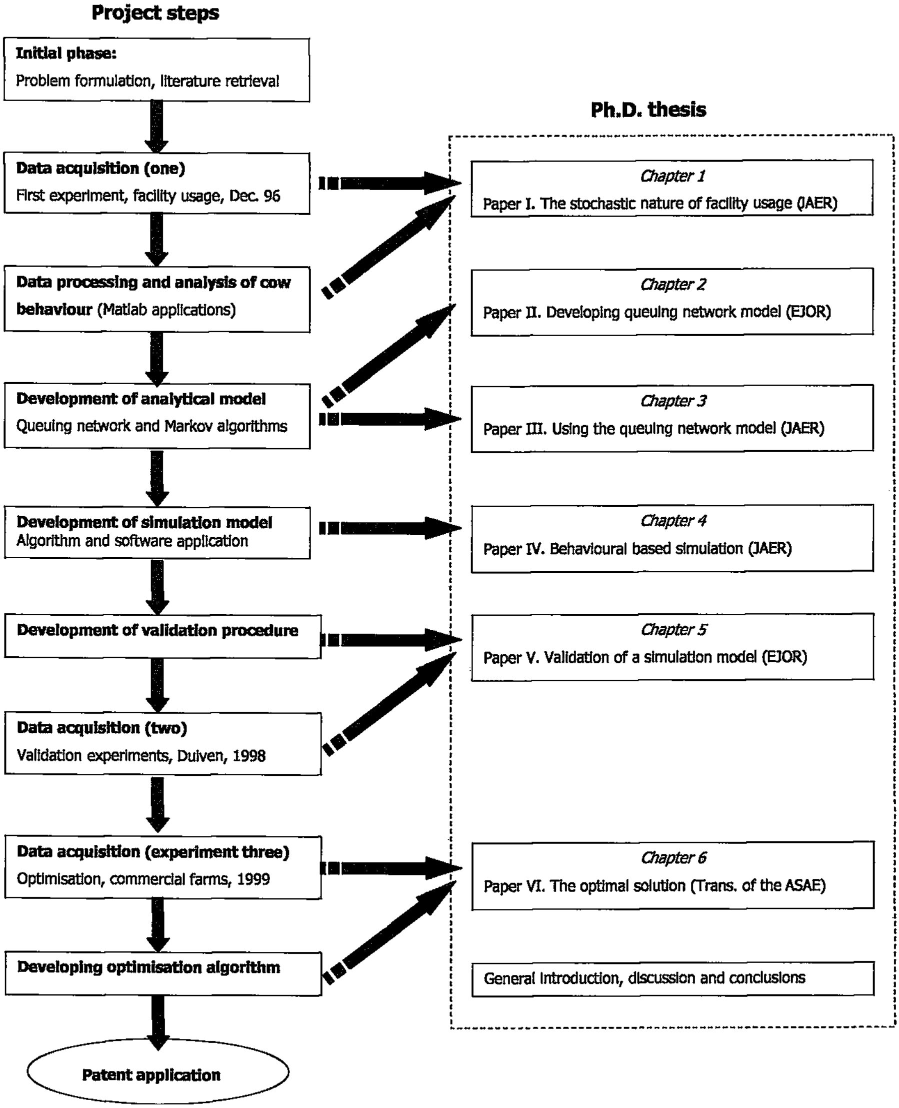

Figure 1. Project planning and evaluation

Note: JAER stands for submitted to the Journal of Agricultural Engineering Research, and EJOR: submitted to the European Journal of Operational Research. Trans. of the ASAE: submitted to the Transactions of the ASAE.

3.1 Animal behaviour requirements (chapter 1)

As mentioned above, getting the cows, operator and facilities to function in harmony is the key to an efficient and successful RMB. However, 'in harmony' is subjective and, therefore not amenable to straightforward scientific investigation, but it is possible to gain insight by observing cow behaviour in various circumstances. For example, one way in which behaviour can be used to give direction to the design process is to find out what the animal itself prefers, by giving the animal freedom of choice and assuming that its activities will tend to cause it less suffering or more positive emotional states. This type of experiment is described in Chapter 1, where the activities of each cow in the group were measured under conditions of allocated over capacity.

3.2 Analytical models (chapters 2 and 3)

Queuing network modelling has been addressed by a many researchers[45,46]. It appeared to be an effective technique for studying the performance of complex manufacturing systems, resource allocation, and complicated interconnections in a system but, until the present study, however, QN had not been used to design barns. Based on the quantification of facility usage in Chapter 1, the development of the closed QN model is described in Chapter 2, and in Chapter 3 its application is demonstrated together with a Markov model.

3.2 Simulation model (chapter 4)

Chapter 4 shows how the limitations of the analytical models can be overcome. The development of behaviour-based simulation (BBS) allows equipment, management practices, farm routines, and layout to be evaluated jointly. It requires fewer simplifying assumptions than the QN model, and animation improves communication between barn operators and designers, allows the farmer to integrate all relevant factors into his model, and highlights potential design options before the barn is built. The main benefit is that before construction work starts, the farmer can be assured that the proposed design will actually work and meet his specified demands.

3.3 Validation (chapter 5)

The general validity of the BBS model is argued and statistically proved in Chapter 5. We conducted three experiments and the resulting data set was compared with the computer simulation. Validation is an integral part of the model's development phases, Figure 2 schematically shows the tied interactions between validation and the development phases during the process of using the proposed design methodology to design a given RMB. Site-dependent parameters such as feeding routine and farmer preferences vary between farms, and were revalidated during each simulation study. For example, a paired-t approach was used for model validation in Chapter 6, and trace-driven validation as recommended by Law and Kelton[36] is presented in Chapter 4,

3.4 Optimisation (chapter 6)

Chapter 6 examines two examples of the acquisition of the optimal solution by the proposed design methodology. We measured two typical farms and developed the equivalent simulation model. Then we observed the simulation responses for selected input combinations, and the regression analysis of the input-output (I/O) data of the simulation directed us to a metamodel I/O transformation[37]. If this transformation happens to be of first or second-order polynomial, Kuhn-Tucker conditions are both necessary and sufficient for obtaining a global solution point[47]. Chapter 6 demonstrates that the extreme points can be found by ordinary algorithms such as projection methods or Simplex.

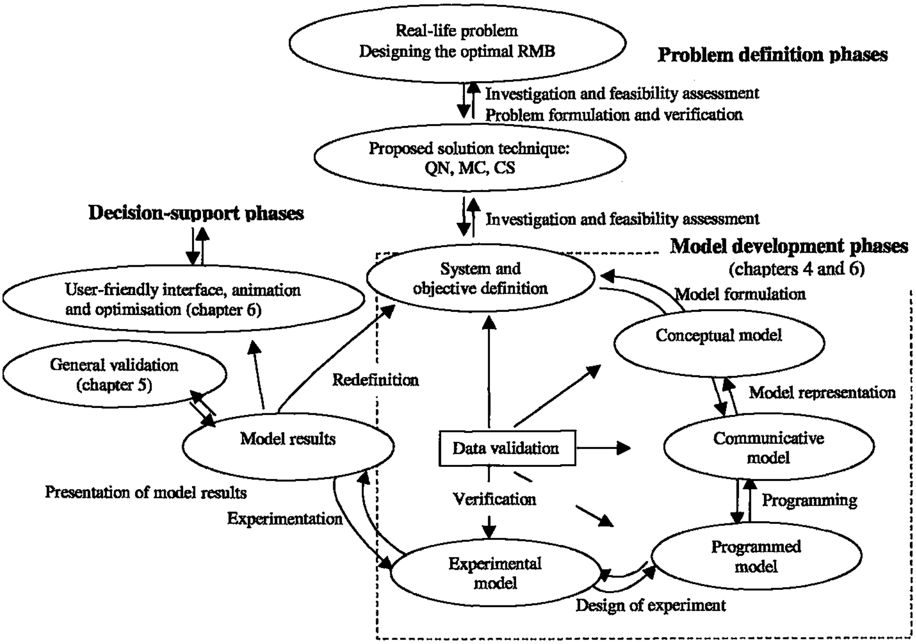

Figure 2. "Life-cycle" of the behaviour-based simulation for investigating a single robotic farm, modified after Banks[48]

3.5 Conclusion (chapter 7)

The newly developed design methodology for the RMB resulted in a practical design tool embedded in a software application, documented by this PhD thesis and protected by a Patent application. The thesis ends with a general discussion and conclusions.

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Chapter 1

Quantifying facility usage

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Abstract

The aim of this paper is to explore the stochastic nature of the usage of facilities in a robotic milking barn, independently of the barn layout. It presents experimental data obtained by monitoring 10 dairy cows over period of 18 days. To minimise restrictions to the access of cows to the facilities, the barn contained less than half the number of the cows for which it was designed. Under these conditions of maximum availability of facilities, the intensity and sequence of facilities usage were studied. The access to all the facilities in the barn can be approximated by an exponential distribution with the parameters: $\theta_{\text{conc.}}=13.15$, $\theta_{\text{Forage}}=8.77$, $\theta_{\text{Water}}=12.06$, $\theta_{\text{Cubicles}}=8.08$, $\theta_{\text{Milking}}=15.11$. The 'flow' of the cows between the facilities was expressed in a transition matrix. The first priority of cows crossing from the resting area to the feeding area through the milking robot stalls was concentrate feeding (91.4% of the events). The occupation rate (cows/positions) of forage lane or cubicles was less than the milking-parlour situation. Robotic milking evened out the usage of all the facilities in the barn throughout day and night to a continuous-time stochastic process.

Quantifying this stochastic process under these conditions of maximum availability of facilities opens up the possibility to allocate facilities optimally, known facility usage by the animals. The next papers present practical models for optimising of the allocation of facilities.

1. Introduction

The use of dairy barn facilities is influenced by management strategies such as batch milking or batch feeding. Under milking parlour conditions, the cows are scheduled by the farmer and the whole group is milked simultaneously (batch milking). Under robotic milking conditions cows are milked not in batches but individually, voluntarily and at any time of day or night (Ketelaar-de Lauwere *et al.*[1]). If the latter results in stochastic milking of the herd, and if robot milking also imposes stochastic usage of the other facilities in the barn, the minimum facility capacity required to satisfy the animals' needs may be affected. However, the nature of this influence is still unknown.

Successful animal husbandry technologies must respect all basic biological requirements of animals involved; and the technical expertise on machines, computer programming, economics and other related fields has to be combined with biological expertise on animal requirements for feed, space, water, *etc.* (Hurnik[2]). There is a long tradition of research on the feeding behaviour and space requirements of cows (Albright *et al.*[3]; Friend *et al.*[4]). Menzi and Chase[5] found that the bunk-feeding lane was fully occupied immediately following the periods of batch milking or group feeding. Livshin *et al.*[6] found that a cow's behaviour in the concentrate feeder was based on the animal's learning ability and quick adaptation to the proposed feeding routine. This suggests that it might be possible to control the cow's behaviour by individual concentrate allocation in a feeding routine. Wierenga and Hopster[7] found that the cows visited the concentrates feeding station throughout the 24-h period, which means that the timing of the visits was not affected by the time of the day. Prescott *et al.*[8] concluded that concentrates rather than forage should be fed in the exit area of the milking robot.

It is important to have sufficient cubicles, because they provide the cows with an opportunity to rest and avoid confrontations. Under normal conditions, cows spend more than 60% of their time in the cubicles - about 13 h lying and 2.5 h standing, Wierenga and Hopster[9]). Gribble and Gribble[10], reported: 'In free stall housing, the beds are of primary importance since a cow spends 10-12 hours per day lying down'. Deprivation experiments showed that dairy cows lying is an important behaviour. A reduction of the number of cubicles causes a decrease in time spent in the cubicles (in particular for the low-ranking animals) and increased number of aggressive interaction as a consequence of the increased competition for lying places (Wierenga and Metz[11]).

The space in between the facilities is used for walking, idling, or grouping. Krohn *et al.*[12] found that in the pasture, during the summer, cows might walk about 2.5 km per day.

A recent addition to the mechanisation of the milking (automatic cluster detaching, automatic udder washing, automatic gates, *etc.*) is automatic cluster attachment by a 'milking robot'. In the Netherlands, there are milking robots in about 45 commercial farms, and it is expected that robot milking will be introduced on a substantial number of dairy farms in the next few years (Rossing and Hogewerf[13]).

When a milking robot has been installed, different management attitudes and operational routines are required. Robotic milking can be used for 'like batch' milking, where cows are milked two or three times daily in fixed periods by the robot. This is seen when farmers insist on keeping their cows on pasture and assemble the herd in a collecting yard before milking and start the milking robot. Alternatively, the milking robot operates continuously and the cows themselves decide when to enter the milking unit (Sonck[14]).

Under continuous robotic milking and continuous feeding, the milking process is spread over day and night (Devir[15]; Ketelaar-de Lauwere and Ipema[16]). Each cow arrives voluntarily, around the clock, depending on her internal biological timing and is milked individually, according to a predetermined individual program. Uetake *et al.*[17] found that robotic milking affects the social synchronisation of cows' eating and resting significantly, compared with parlour milking.

In contrast to the 'individuality' that is inspired by the robot, 'cows prefer to eat, rest and perform many other activities in a socially synchronised fashion' (Hurnik[2]). Animals within a herd do not act independently of each other, but more like a co-ordinated social unit with social hierarchy (Kondo and Hurnik[18]). Therefore in a robotic milking barn, there is a 'trade off' between the socially synchronised activities and the individual activities of the animals. This needs to be quantified. In order to do so, the usage of barn facilities by dairy cows and their behaviour under defined conditions has to be studied and modelled.

If facilities usage by dairy cows is a continuous-time stochastic process, queuing theory and Markov chains could be useful to model it, for the purpose of designing service facilities (layout) in a barn. The situation can be described by 'cows forming queues in front of service facilities', and the language of queuing theory can be used for modelling. Individual facilities, *e.g.* concentrate feeder, water troughs, milking robot are 'busy' when a cow is being 'served' or 'idle' when no cow is present. Three major aspects are involved when applying queuing theory in practice: (1) special demands on data; (2) selection of an appropriate mathematical model representing the real system; and (3) implementation of a decision model based on system performance.

The distributions of arrivals and service times principally determine which queuing model is appropriate (Taha[19]; Hillier and Lieberman[20]). To determine these distributions, the queue system has to be observed and the appropriate data have to be recorded. The nature of the process should be analysed and described mathematically, from this, the appropriate modelling technique can be identified.

In the barn, two questions arise: when to observe the system and how to collect the data. Most queuing situations have 'busy' periods, during which the arrival rate is higher than at other times of the day. For example, incoming traffic on the main motorway peaks during rush hours. In a situation like this, it would be necessary to collect data during the 'busy' period and to design the motorway for these extreme conditions. An equivalent in the barn is the busy period after traditional milking, when all the cows leave the milking parlour in groups, or during feeding when all the cows 'rush' to the feeding bunk. Current facilities in parlour milking barns are built to meet these extreme conditions, which may not apply to the robotic milking barn. It can be expected that robotic milking and continuous feeding deviate from this extreme queue situation since they spread the milking period over the day and night. Accordingly, the barn design may have to be changed. 'The concept of systems engineering will play an increasing important role in design of future livestock systems. Systems theory needs to be employed to handle the myriad of processes that exist in livestock enterprises' (Scott[21]).

Queuing theory has revolutionised the design of computer networks, telephone networks, banks, supermarkets, *etc.* If this theory also inspires barn design, it will be seen as a significant development. By quantifying the usage of facilities as a stochastic process, this research attempts to show a way of using systems theory like queuing and Markov chains, when designing robotic milking barns. The objective of the research described in this paper was to quantify the intensity and sequence of facilities usage by the cows in a robotic milking barn, under conditions of maximum availability of facilities, in order to define the probability nature of the process, as a first step towards optimising facilities allocation.

2. Materials and methods

2.1 Experimental details

Ten cows were kept in a slatted-floor, loose housing with cubicles, originally designed for 26 cows. The barn contained two milking-robot stalls (Prolion Ltd.) combined with internal concentrate feeders; an automatic roughage feeding system with 14 troughs; one concentrate self-feeder and 26 cubicles and three water troughs that could be easily approached by the cows in all sections of the barn's (see *Fig. 1*). All the facilities were visible from anywhere in the barn. A one-way gate between the concentrate self-feeder and the forage food area forced cows to reach the concentrate feeder via the robot direction. Identification antennas were installed in each facility (server function) of the barn and between activity areas. The cows (Holstein-Friesian and Friesian Holland) were accustomed to the facilities, routine and well into lactation (two or more months). Two cows were in their first lactation, six cows in the second lactation, one in the third , one in the fourth lactation. Average body weight was 650 kg for adults and 550 kg for first lactation; average milk yield was 35 kg/d contain 4.28% fat and 3.3% protein. The cows were selected for their good cluster attachment in robot milking. The experiment was carried out during 18 days, in Dec. 96, in the IMAG-DLO experimental farm, 'De Vijf Roeden', at Duiven, The Netherlands. The average daily outside temperature was 1.3°C.

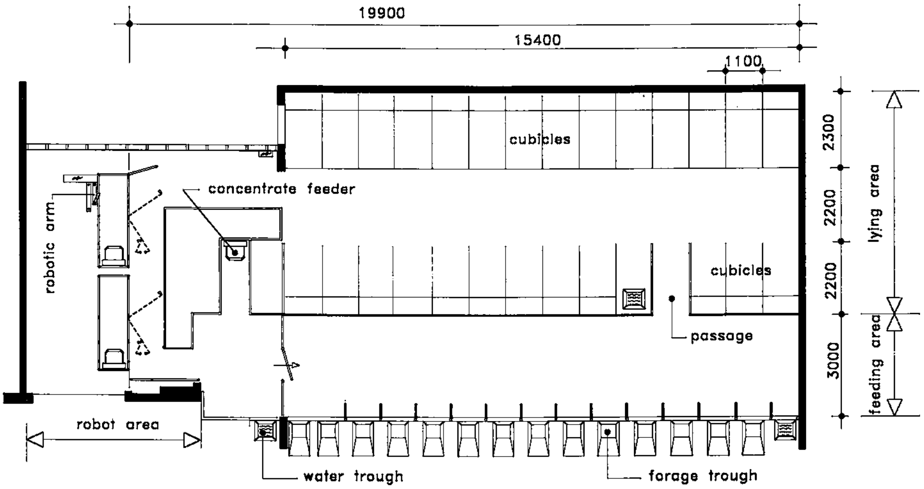

Fig. 1. Layout of the barn; dimensions in mm

The cows were offered a mixed roughage ration containing 68% grass silage and 32% maize silage. Providing average of 7.2 MJ of NE_L per kg, and 194 g of CP/kg (on dry matter basis) for ad libitum intake at the troughs. The troughs were refilled every 30 min when needed. The cows received 8 kg concentrates per day in the concentrate feeder and one kg/milking in the milking robot. A feeding time-window of the concentrate feeder started every six hours - at 0:00, 06:00, 12:00 and 18:00 hours. If a cow entered more than once within a 6-hour period after the predefined fixed amount of concentrate had been dispensed, she was not offered any concentrate. Any left-over was added to the next period. The robot was maintained and cleaned daily between 19:30 - 20:00 hours, milking frequency was limited to four times per day, with more than 6 hours between consecutive milkings. If a cow entered the milking robot more than once within a period, it was not milked, no concentrate was offered and it had to proceed to its next destination.

2.2 Data acquisition and analysis

Individual information on all physical activities (feeding, drinking, milking, staying in cubicle) and all movements from one area to another were recorded automatically. Cubicle usage was recorded on video 24 hours per day. Data on arrivals and departures were obtained by collecting the clock time of facilities operation. The time between successive arrivals was recorded to obtain interarrivals of usage and idle-time. After discarding faulty measurement and the first five regulating days, the database contained 36531 events. A computer program was written in Matlab (Mathworks Inc.[22]) to process the raw data.

A service facility was defined according to its function, *i.e.* the 24 cubicles were one service facility (with a capacity of 24 parallel servers), the single self-feeder was one service facility, the double-stall milking robot was one service facility, *etc.* Since cubicles should be designed with an extra space in front of them (to allow entrance), a cubicle was defined as 1.1 by 3.3 m (an extra 1.1 metre longer). This implies that the passage in front of the cubicles was defined as part of the cubicles (see *Fig. 1*).

Forage was consumed in meals during day and night; a meal was divided into bouts - see Metz[23] for a definition of a bout at behavioural level. The 'if-then' algorithm was the following: 'Two successive accesses (bouts) by the same cow at the same facility were counted as one access including the length of the interval between them *if* one of the following holds: (1) either the access period was longer than the interval or (2) the interval was shorter than 10 minutes'.

The approach was similar to the method used by Metz[24] and Morita *et al.*[25], but the new algorithm was easier to program in a computer language.

To gather the information so that associated probability distributions could be determined, the observations were summarised in a form of distribution histograms, in terms of frequency, probability density function (f_{pd}) and cumulative distribution function (f_{cd}, Mathworks Inc.[26]). Since we were dealing with time, the data were treated as a continuous case. For the purpose of queuing modelling, the negative exponential distribution was applied.

The probability density function is: $$fpd(x)=\frac{1}{\theta}e^{-\frac{x}{\theta}},\quad \theta>0, x>0 \qquad (2)$$

The cumulative distribution function is: $$fcd(x)=1-e^{-\frac{x}{\theta}} \qquad (3)$$

resulting in $$ln(1-fcd(x))=-\frac{x}{\theta} \qquad (4)$$

Where the parameterθ is the exponential rate. When 1-$f_{cd}(x)$ is plotted against x on a semi-log scale, the plot is a straight line. If the negative exponential distribution is an adequate model for the empirical data, then the straight line should fit the observed points (Agostino and Stephens[27]).

Apart from graphical 'goodness of fit' for exponentiality, the distributions were tested against fit to the family of gamma distributions, where the distribution with parameter b equal to 1, corresponds to an exponential distribution (Haccou and Meelis[28]). Estimates were given for the parameter b of the gamma distribution with its standard errors (se). Cases for which parameter values 1 were either within or near the confidence interval were regarded as exponential. The maximum likelihood for the exponential rate θ of these cases was estimated.

In order to achieve a reliable quantification, the data analysis had five stages:

(1) actual use of the facilities;

(2) relations between milking and the usage of other facilities;

(3) transition between facilities;

(4) periodicity of facility occupation;

(5) facility usage distributions.

3. Results

3.1 Actual use of the facilities

Figure 2 presents the individual resolution of data collected. It can be seen that: (1) These cows spend much more time in the cubicles than in other facilities; (2) forage was consumed in meals throughout day and night, each meal being divided into bouts (each vertical line is a starting or ending of one bout); and (3) a meal is a combination of several sequential activities (concentrate eating, forage eating and drinking).

An occupancy rate of the forage-lane positions and cubicles is presented in *Fig. 3*. It can be seen that: (1) the cubicles were used more than the forage lane and more cubicles were used simultaneously; and (2) the use of these two facilities was less than 100%, *i.e.* on this typical day (*Fig. 3*), the cows never all used one facility simultaneously. A high occupation rate was rare during the entire experiment too (*Fig. 4*); in only 2% of the occurrences were more than 6 cows in the forage lane at the same time, and in only 5% of occurrences were more than 8 cows in the cubicles at the same time.

3.2 Relations between milking and the use of other facilities

After leaving the robot, the cow was free to choose its next destination without traffic limitations. Inter-relations between milking-robot and the usage of other facilities were estimated by measuring the interval between leaving the robot and arrival at another facility. In 80 % of the cases, the cows reached the concentrate self-feeder within five minutes (*Fig. 5*). In 80% of the cases, cows reached the forage lane within 22 min, the cubicle area within 35 min, and the water troughs within 100 min. In spite of some variation between individual cows (see table 1), all the cows found the concentrate self-feeder the strongest attraction in the barn. Table 1 confirms per individual cow that this feeder was the first target of a cow when leaving the milking robot. It can be seen that this phenomenon was the case for all the cows.

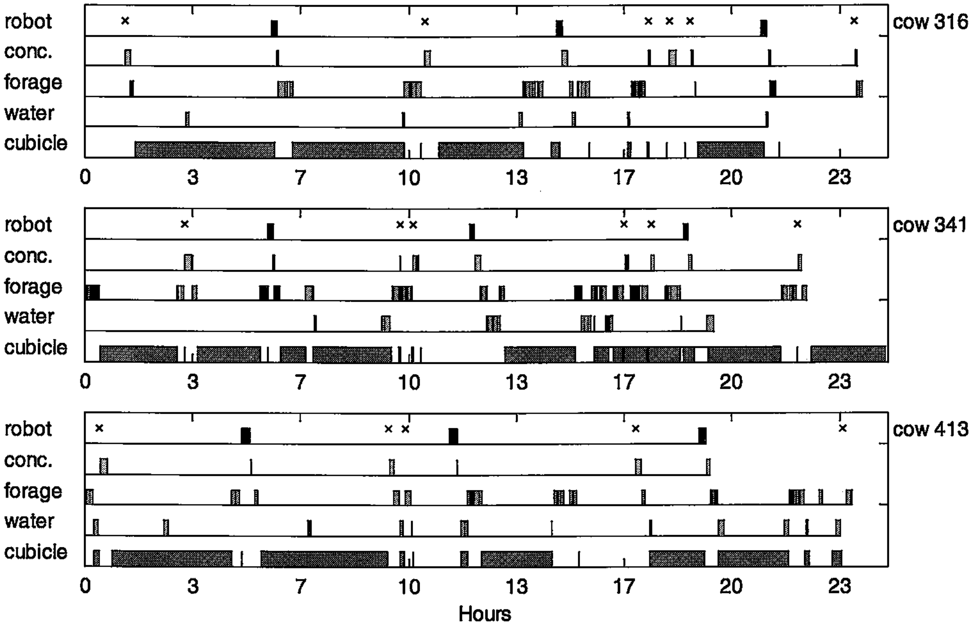

Fig. 2. Three typical records of facilities usage by individual cows during 24 hours; x, walking through the robot (without being milked)

3.3 Transition between facilities

For formal methods derived from the Markov chain, it is important to know whether or not the facilities in the cowshed are used sequentially (Haccou and Meelis[30]), *i.e.* if a behavioural act (j) is followed by act i and the frequency for each pair of subsequent acts (j and i). The frequencies are given in Table 2. It can be seen that the 'popular' movements occurred between the forage lane and the cubicles, from the cubicles to the milking robot and from the robot to the concentrate-feeder.

3.4 Periodicity of facilities occupation

From *Fig. 6*, it can be seen that the use of concentrate feeder, forage lane, water troughs, cubicles and milking robot was spread over day and night. The usage of the facilities was quite stable (small fluctuations) and continuous (*Fig. 6b-6e*). Activity in the forage lane had a more intense period around 17:00h (*Fig. 6b*), and the usage of cubicles during night hours was longer (*Fig. 6e*). The use of water troughs and milking robot had no main busy periods (*Fig. 6c-6d*). The access to the concentrate feeder (*Fig 6a*) corresponded with the feeding time-windows mentioned above.

3.5 Distributions of facilities usage

Graphical 'goodness of fit' (Mathworks Inc.[28]; Agostino and Stephens[29]) was applied in order to fit exponential distributions to the observations of facilities usage. It can be concluded (*Figs 7a-e, 8b, 8c,* Table 3), that the intervals between successive use of all the facilities and the duration of use of forage feeding lane and water troughs could be reasonably described by exponential distribution.

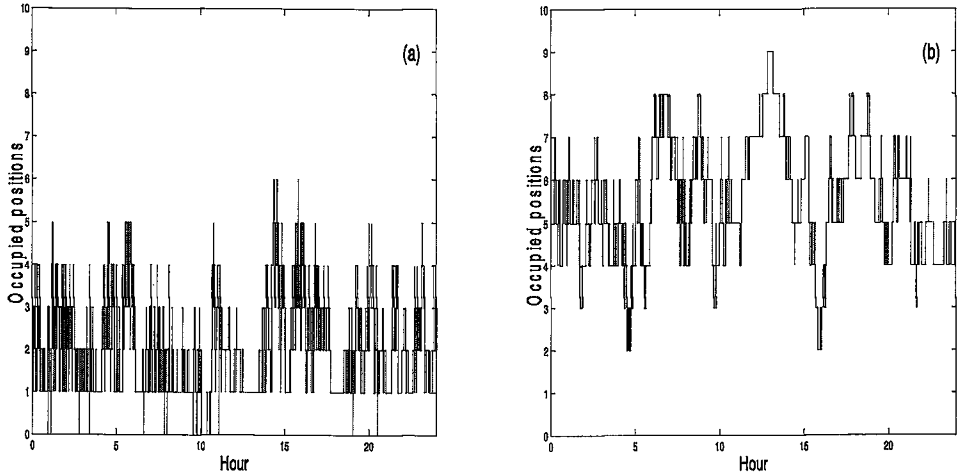

Fig. 3. Occupancy rate distribution of forage lane (a) and cubicles (b) over a typical day

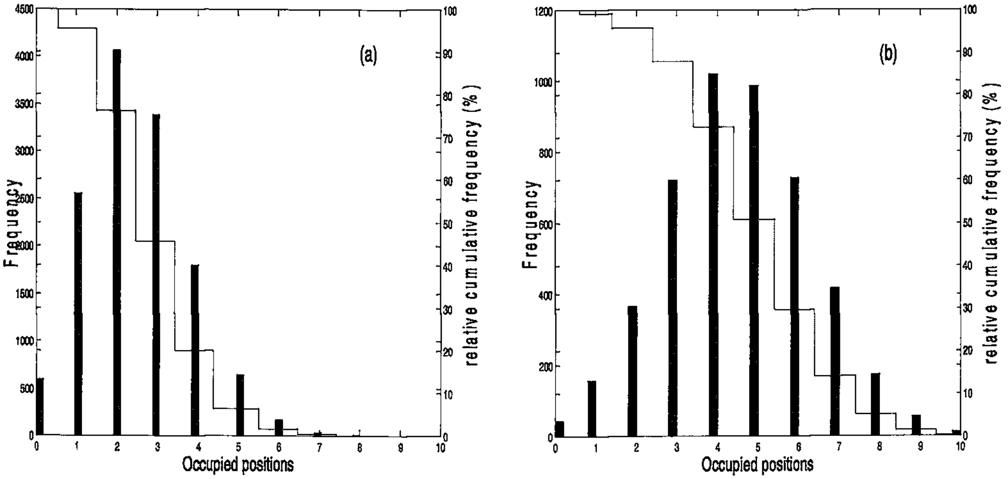

Fig.4. Occupancy distribution of forage-lane positions (a) and cubicles (b), during the experiment; occupied positions is the number of forage-lane positions or cubicles used simultaneously by the cows; bar graph, frequency; stairs plot, cumulative frequency distribution

Table 1: First target of an individual cow when leaving the milking robot: total number of arrivals and arrivals at each facility

Cow ID number	Lactation	Milk yield kg/day	Total Arrivals	Arrivals at each facility (%)			
				Concentrate	Forage	Water	Cubicles
128	4	42	166	94.58	3.01	0.60	1.81
219	3	41	61	91.80	8.20	0.00	0.00
316	2	29	147	96.60	2.04	0.68	0.68
317	2	35	148	85.81	4.73	0.68	8.78
324	2	37	173	94.80	2.89	0.58	1.73
341	2	38	137	93.43	5.84	0.00	0.73
331	2	32	143	94.41	2.10	1.40	2.10
306	2	33	125	94.40	2.40	0.80	2.40
413	1	27	106	83.96	11.32	2.83	1.89
426	1	35	122	80.33	14.75	0.00	4.92
Sum of all cows			1328	91.42	5.20	0.75	2.64

ID, identification

Table 2: Frequency of transitions between facilities in the barn

Departure facility (from...)		Frequency of movement to barn facilities (to...)				
		Concentrate (1)	Forage (2)	Water (3)	Cubicles (4)	Milking (5)
Concentrate	(1)	37	804	138	310	5*
Forage	(2)	9*	67	310	1515	23*
Water	(3)	29	617	140	204	381
Cubicles	(4)	5*	364	779	171	917
Milking	(5)	1214	69	10	35	15

* The measurements 'from forage to concentrate-feeder' (2,1), 'cubicles to concentrate-feeder (4,1)', 'concentrate-feeder to milking (1,5)' and 'forage to milking (2,5)' are not equal to zero because of technical failures, in a cow identification at the robot site and in the cubicles. They should be zero because of the one-way gate in the barn layout. The value 'milking to milking (5,5)' might have happened when a cow attempted to be milked in the first stall of the robot, cannot be attached, but then entered the second stall in the same visit.

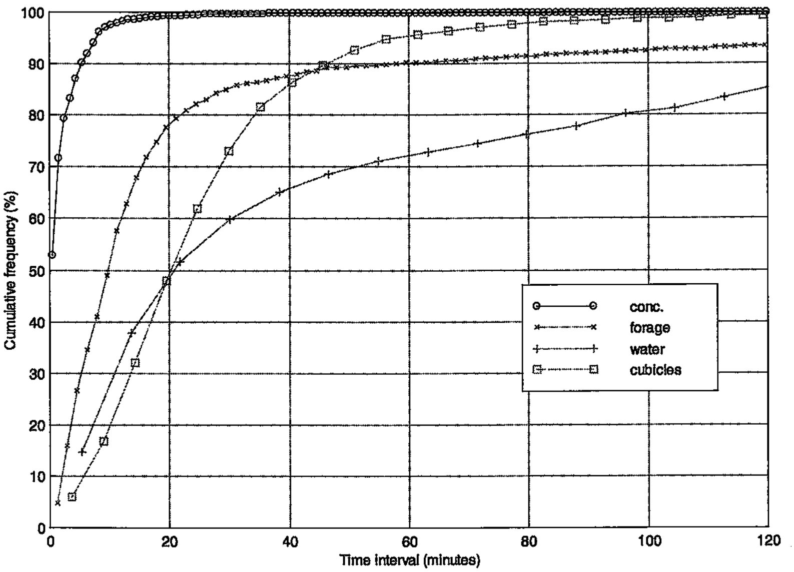

Fig. 5.Cumulative frequency of the intervals between leaving the robotic milking stall and arriving at another facility (concentrate feeder, forage lane, water troughs, cubicles)

It can be seen that the duration of use of the concentrate feeder (*Fig. 8a*) was a mixture of two different distributions (two clear extremes). It was possible to separate these two distributions by linking the data to the event 'got food or not'; see Table 3.

The duration of cubicle use (*Fig.8d*) was, like the concentrate feeder, derived from two distributions: cows that lay down (mean duration around 100 minutes) and cows that went through on their way to the robot milking, or started off, changed their mind without lying down and went back to the forage yard. The duration of use of robot milking stalls (*Fig. 8e*) is not an exponential distribution.

Apart from graphical inspection (*Fig.* 7 and 8), the data were tested against the fit to gamma distributions (Table 3). It can be seen that 'inter-arrivals' of all the facilities and the duration of use of forage lane and water troughs could approximately be expressed by exponential distributions. These results agree with the graphical fit, for these cases, a maximum likelihood estimate is given for the exponential rate θ to be used in designing the optimal robotic milking barn[29].

Table3 : 'Goodness of fit' of gamma and exponential distributions for interval between use, and duration of use of different facilities

Facility	Gamma distribution			θ(exp.)	Mean(min)	std(min)	Dist.
	Deviance(df)	b	se(b)				
conc,int,2	135(33)	1.456	0.052	13.15	13.76	12.15	E
conc,dur,2	476(33)	1.120	0.039	4.54	6.38	6.25	G
conc,int,0	47(11)	0.927	0.082	26.55	22.30	35.52	E
conc,int,1	167(18)	0.992	0.058	31.94	28.32	30.33	E
conc,dur,0	341(24)	1.088	0.051	3.49	3.37	4.99	E
conc,dur,1	273(22)	3.208	0.176	5.38	9.74	5.78	G
forage,int,2	52(43)	0.986	0.026	8.77	9.17	8.68	E
forage,dur,2	84(43)	1.156	0.031	11.04	15.01	11.95	E
water,int,2	78(35)	1.108	0.037	12.06	13.31	12.31	E
water,dur,2	36(35)	1.865	0.065	2.71	3.18	2.30	E
cubicle,int,2	850(54)	0.654	0.014	8.08	8.34	8.01	E
cubicle,dur,2	2267(35)	0.265	0.005	59.42	38.85 (60*)	60.32	G
robot,int,2	18(7)	1.167	0.078	15.11	13.42	13.42	E
robot,dur,2	28(2)	12.40	0.92	3.25	8.41	2.53	G
robot,int,01	12(18)	1.137	0.067	41.72	39.49	37.42	E
robot,dur,01	---	---	---	---	8,84	2.23	---
robot,int,00	4(2)	1.413	0.331	---	23.62	20.82	E
robot,dur,00	---	---	---	---	3.10	0.76	---
Walking.int	---	---	---	---	6.50	20.06	---

int, interval between successive use; dur, use duration; 0, no concentrate was offered; 1, concentrate was offered; 2, all the cows; 01, only the cows that were actually milked 00 un-milked visit;

Dist., type of distribution: E, treated as exponential; G, treated as 'non exponential distribution namely 'General distribution'; *b,* the parameter of the gamma distribution with its standard errors (se); *θ,* the parameter of exponential distribution; *df,* degree of freedom.

* According to the definition of cubicles as a 'one service facility', a cow which just goes through the cubicle area is accounted for as being in cubicle area. Usually, if a cow lay-down it takes longer than 1min. Therefore after cleaning the measurements 'less than 1 min' the average 'service-time' becomes about 60 minutes.

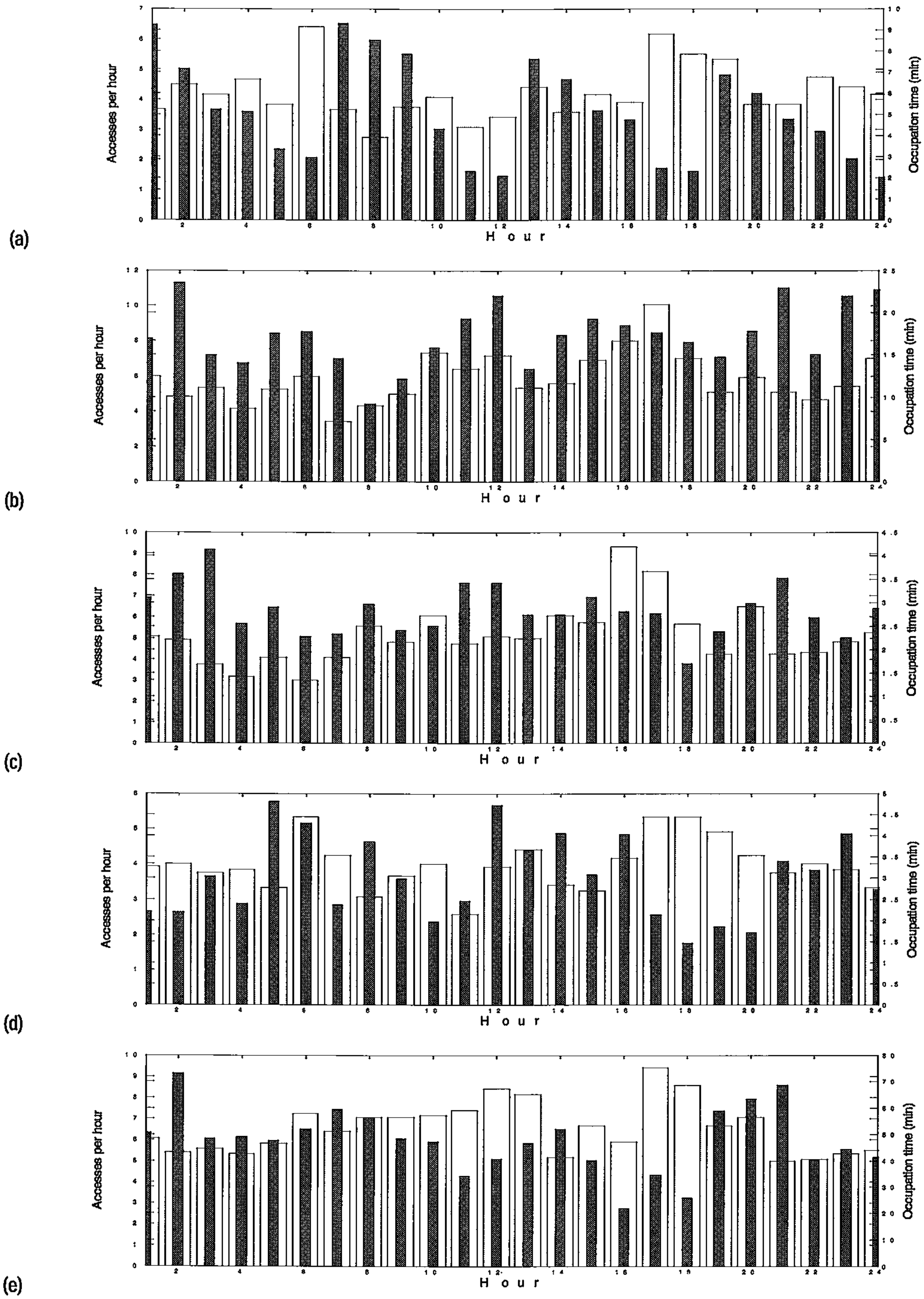

Fig. 6. Periodicity in number of accesses (□) and duration of use (▮) of concentrate feeder (a), forage feeding lane (b), water troughs (c), robot milking stalls (d) and cubicles (e). Each column presents use during a specific hour (X axis). 'Accesses' gives the number of times that the facility had been approached and the 'duration' gives the average duration of each visit in minutes

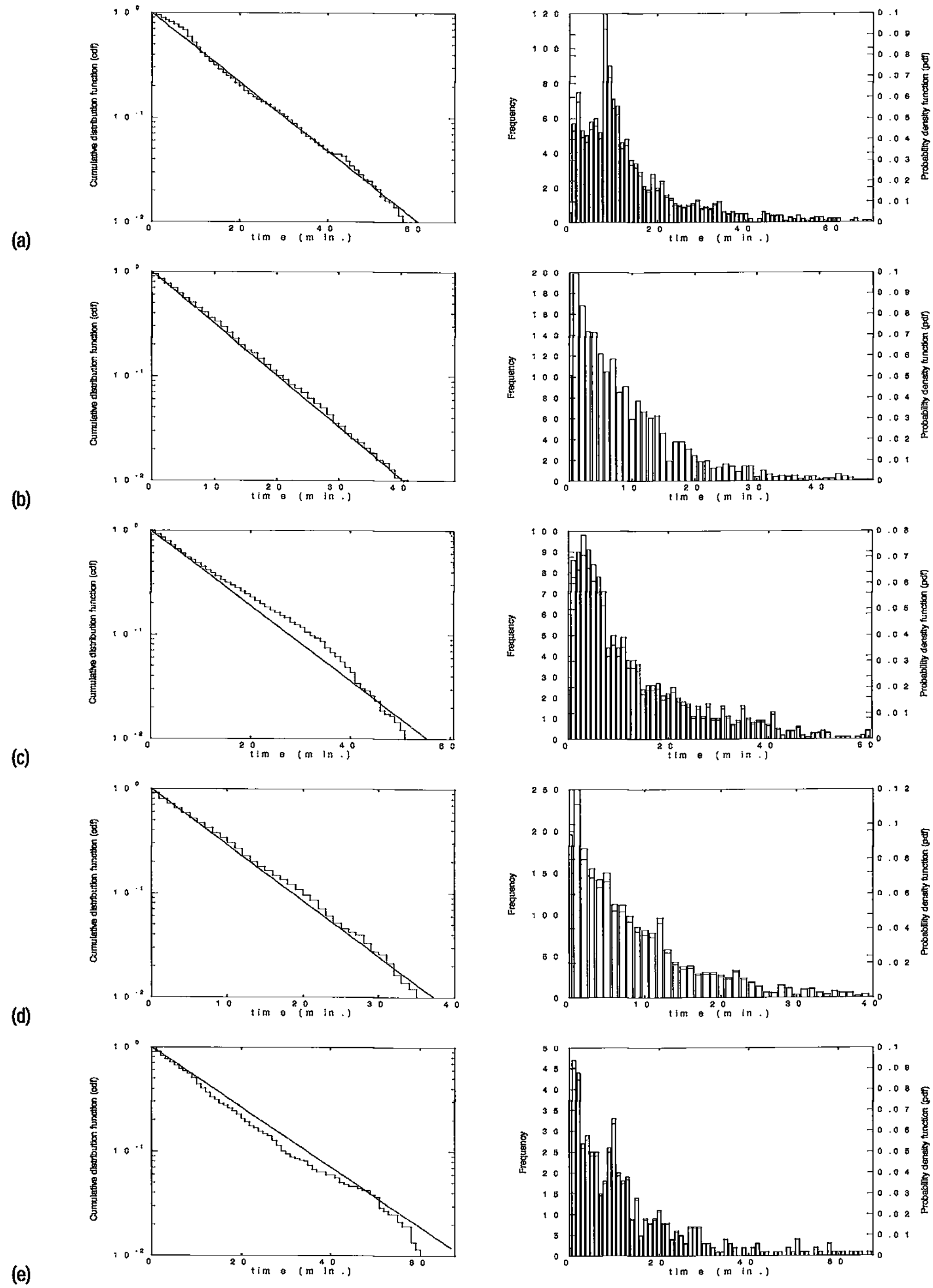

Fig. 7. Frequency, density and cumulative distributions of intervals between successive use of concentrate feeder (a), forage feeding lane (b), water troughs (c), cubicles (d) and robot milking stalls (e)

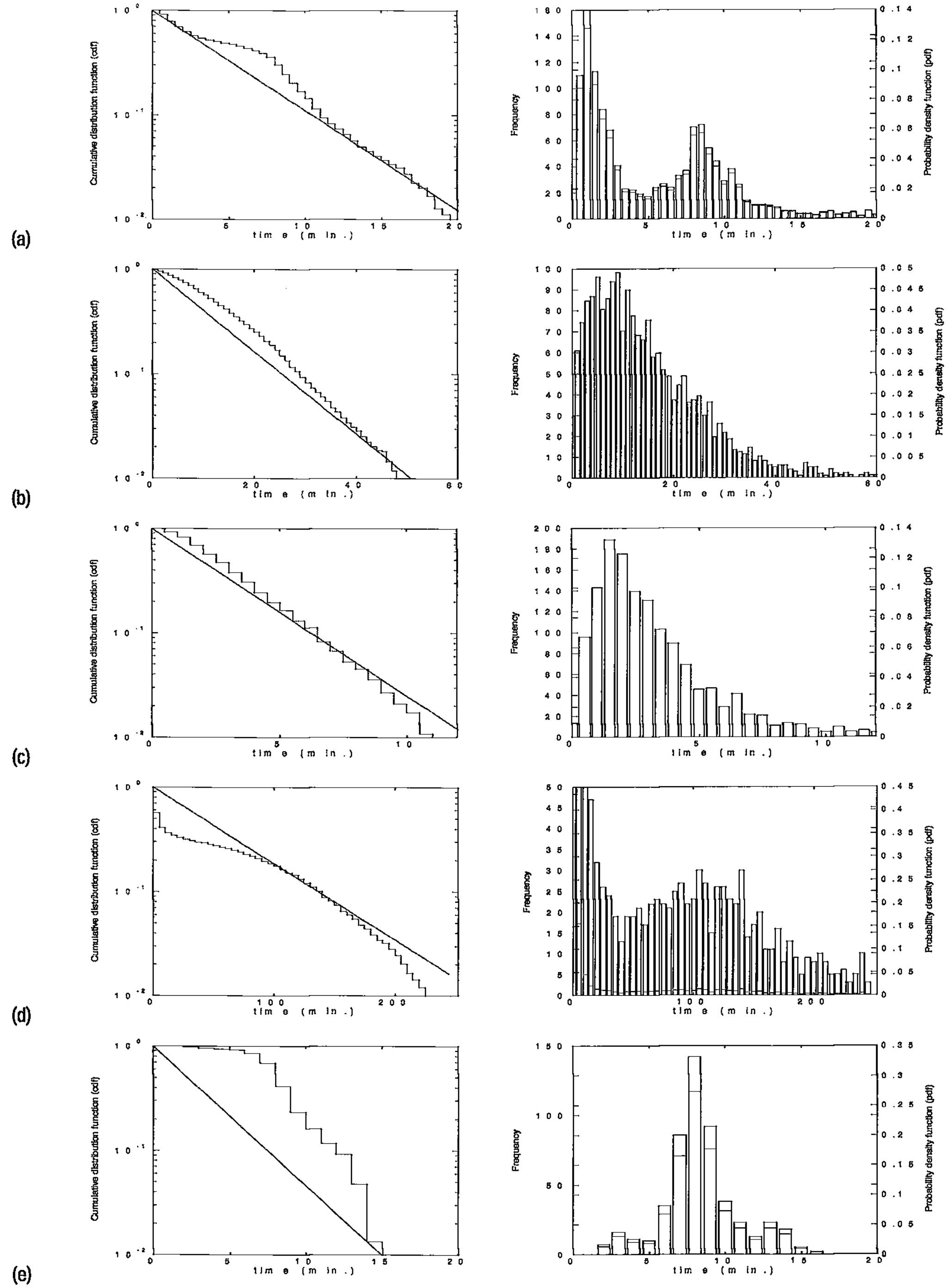

Fig. 8. Frequency, density and cumulative distributions of the duration of use of concentrate feeder (a), forage feeding lane (b), water troughs (c), and cubicles (d), robot milking stalls (e)

4. Discussion

The facilities usage was observed under the condition of minimal restrictions to cow access. This was achieved by reducing the ratio 'cows per facility' to less than half of the ratio the barn was designed for, in order to have no pressure on bunk feeding or resting space at any given time, while keeping a sufficient number of cows as a herd. From the occupancy rate of forage lane and cubicles (*Figs* 3 and 4), it can be concluded that the number of positions in both facilities could be reduced without restricting their availability to the cows. By simple visual analysis, it is possible to estimate an 'upper limit' for animal requirements for forage lane and cubicle allocation (for example, it was rather rare for more than six cows to use the forage lane simultaneously or for more than eight cows to be in the cubicles).

Obviously, this was not the case for the single concentrate self-feeder, the double milking stalls and drinking troughs. Because of their different nature of function, there were more cows than positions. Nevertheless, the number of cows for each position of these facilities was far less than current recommendations. Conclusions about optimal ratios (cows per position) for these three facilities should be determined after studying their occupation rate and how they are used by the cows[9,10].

The optimal number of cubicles and forage positions will vary from herd to herd, depending on total exercise area, season and physical layout. If empty free stalls are seen, it is likely that cows use them efficiently (Friend *et al.*[7]). Herd size also affects the social stability and associated behaviour (Kondo and Hurnik[21]).

In 80% of cases, the cows reached the forage lane within 22 minutes. This might also cause some aggressive behaviour under conventional milking parlour conditions, even if there are sufficient feeding positions in the lane (refer to Morita *et al.*[27]).

The experiment was performed during December in the Netherlands, it is assumed that under hot summer conditions of a hot climate and drier food, the pressure on the water device may be higher.

The rather short interval between use of the milking stall and the concentrate feeder and the phenomenon that the first target of ***all*** the cows (when leaving the milking robot) was the concentrate feeder imply the strong relation between these two facilities. This indicates that the main reason for going to and through the robot milking facility is the desire to get concentrates, either in the milking stall or in the concentrate feeder, and suggests that the concentrate feeder is an effective way to force routing.

Similar to the findings of Livshin *et al.*[9], the access pattern to the concentrate self-feeder corresponded with the feeding time-windows. This implies that the activity period was spread over the day and night by the pre-defined time-windows of the concentrate self-feeder. It is common knowledge that in milking parlour husbandry, most of the cows are 'pressuring' the feeding facilities after milking. It is also known that there is pressure on the concentrate-feeders when a feeding period starts (Livshin *et al.*[9]). In our experiment, the undesired situation of all cows arriving simultaneously at specific hours (after the milking) was avoided.

It is expected that cows will feed after milking and that their preferred food is concentrates (farm observation). Hence, it is likely that under milking parlour conditions, *i.e.* when a group of cows leaves the milking parlour at the same time, the pressure on the concentrate feeders will be much higher than under robotic milking conditions. The concentrate feeder area will be over crowded, and aggressive behaviour is to be expected. This impairs the 'animal welfare'.

The observation that meal duration in concentrate feeder has a distribution with two clear extremes is a consequence of the nature of concentrate-feeder use. Two different distributions could be distinguished – the duration for cows that were allowed to eat (a mean of about 8 minutes), and the duration for cows that were not allowed to eat (a mean of one minute). Refused cows, which tried the concentrate feeder and left, took less than one minute to do so. Cows that tried the concentrate-feeder, received food and stayed to eat took about eight minutes.

The average duration of milking in this experiment was 8.84 min. The occupation of the milking-robot that lasted less than four minutes, resulted from cows that were 'just going through' (a cow that arrives at the robot but is not milked). If a cheaper 'selector gate' or 'selection units' (Stefanowska *et al.*[30]) could perform this simple traffic control, the robot efficiency could be improved.

The concept that there can be an 'ideal' livestock system is difficult to comprehend, although an 'ideal' system design may exist in a particular situation. The 'system', comprising barn facilities, cows, *etc.* has state changes connected to a certain moment in time and results from the initiation of complicated activities. Then it is defined as a '*discrete-event dynamic system*'. We assume, an 'ideal' system design may exist in a particular situation, it may not suit any other. The optimal ratio of facilities allocation to the number of cows and the balance between facilities should be calculated using the system performance that was characterised in this research. For example, see Halachmi *et al.*[31-33].

5. Conclusions

In the robotic milking barn, with cows fed continuously round the clock and maximum availability of facilities (the conditions of this study), it can be concluded that:

(1) facilities usage in the barn is a continuous-time stochastic process, spread throughout day and night;

(2) the cows' access (arrival time) to all the facilities can be represented as an exponential distribution;

(3) the occupation time of each visit (service time) of forage lane and water troughs can be represented as an exponential distribution;

(4) the service time of the milking robot, concentrate feeder and cubicles is derived from two mixed distributions, being distinguished in the milking robot and concentrate feeder by using the milk yield and the amount of concentrate consumed in each visit;
(5) the interrelation between facilities usage can be formulated in a transition probability matrix;
(6) compared with traditional loose housing husbandry, it seems that there are too many forage lane positions and cubicles;
(7) the main reason cows visit the milking stalls is their expectation to have concentrates; this might be exploited as the only tool to force them into a routine.

The facilities usage can be explained by the nature of the milking robot operation and the interrelations between the barn facilities. The exact allocation of barn facilities may be determined according to the animals' needs (biological, physiological, sociological, *etc.*) as found in this experiment.

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Chapter 2

Developing a queuing network model

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Abstract

In this paper we present a closed queuing network model for a robotic milking barn. We use an approximate mean-value algorithm to evaluate important performance criteria such as the number of cows waiting, their waiting time and the utilisation of the facilities in the barn. It is shown how the results from the queuing network analysis can support the discussion about optimal design of the robotic barn.

Keywords: design of dairy barns, milking robot, queueing network, approximate mean value analysis

1. Introduction

The most important recent development in the dairy industry is robotic milking. Dairy barns with milking robots are becoming more and more interesting from an economical point of view, cf. Dijkhuizen[1]. Today already over 200 robots have been on installed on commercial Dutch farms. As robotic milking barns (RMB) are expensive, it is important to develop models which make it possible to discuss the optimal layout of an RMB and the optimal capacities of the various facilities in the barn depending on the herd size before actually constructing it.

In an experimental farm in Duiven in the Netherlands the agricultural research center IMAG-DLO is investigating the behaviour of the cows in an RMB. Based on extensive measurements and observations, it was in Halachmi at el.[2] concluded that it is necessary to incorporate the stochastic behaviour of the cows in the design of an RMB. Another aspect, which makes this design complex, is the interaction between the facilities in the barn: increasing the capacity of bottleneck facilities will shift queues and alter the location of bottlenecks, possibly forcing the designer to increase the capacity elsewhere. The concept of the closed queueing network(CQN) seems to be very appropriate for modelling and analysing an RMB. It covers both the random behaviour of the cows and the interaction between the queues. It also supports a systematic analysis of the economic tradeoffs. The CQN model is widely used in the communication systems and production systems areas. The present application area, the design of RMBs, is new. As we will see, it is a potentially powerful design tool here as well.

In section 2 we briefly describe the milking robot. In section 3 we look at the RMB and we introduce the CQN model. We discuss the data that are needed and we already formulate a number of performance criteria that are particularly important in this application. In section 4 we present the approximate mean-value analysis of the CQN. This approximation technique is validated in section 5 by comparing it with simulation of the CQN model. The simulation uses real data collected in the experimental barn in Duiven. In section 6 we show how the results from the CQN analysis support the discussion about the possible designs of the barn. In section 7 we spend a few lines on the Java applet that has been build for this application. The final section is devoted to conclusions and comments.

2. The milking robot

The milking robot is shown in figure 1. Milking robots are different from the ordinary milking machines in one crucial aspect: the robot uses sensors to find the teats of the cow and then connects the cups to the teats with a robot arm.

There are at least two good reasons for using robots. First, it saves a serious amount of labour and second, it makes it possible to go from milking twice a day to three or even more times a day. When cows are milked three times a day their production is increased by about 15 percent. Milking robots, their operation and costs have been reviewed elsewhere, see e.g. Rossing et al.[3],Sonck[4], and Devir[5].

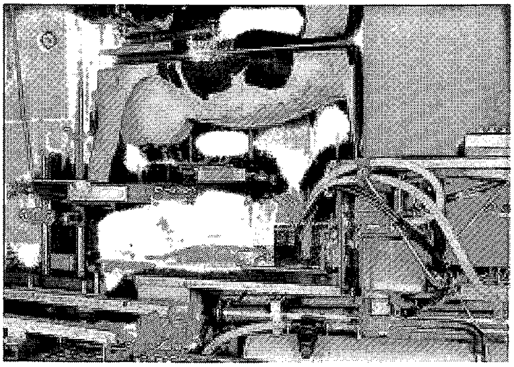

Figure 1: A milking robot

3. The RMB and the CQN

In this section we describe the RMB, formulate the CQN model and discuss some of the performance aspects.

3.1 The RMB

The basic layout of the RMB we are dealing with is shown in figure 2. In the barn we distinguish five facilities or servers.

- The Milking robot.
- The second one is the Concentrate feeder. Each cow is allowed to receive only a limited amount of `concentrate'[6]. So the Concentrate feeder must have the equipment to be able to identify the cows and to decide how much concentrate to give to the cow. Cows are very fond of the concentrate. Therefore the Concentrate feeder can be and is used to get the cows to pass through the Milking robot. In the present design in Duiven the cows can only reach the Concentrate feeder via the robot.

The three more conventional facilities are:

- The Forage lane. Forage lanes are cheap. There are no limitations on foraging. The only condition is that there must be enough eating positions at the forage feeder to prevent the cows from becoming aggressive.
- The Water troughs. A `high-yielding' cow may drink upto 180 liters a day. Water throughs are cheap, but of significant physiological importance.
- The Cubicles. In the cubicles the cows can lay down, rest, and avoid confrontations. They spend roughly 50 percent of their time in the cubicles. Cubicles only require space, some fencing and bedding material (wood shavings, sand, rubber mattresses).

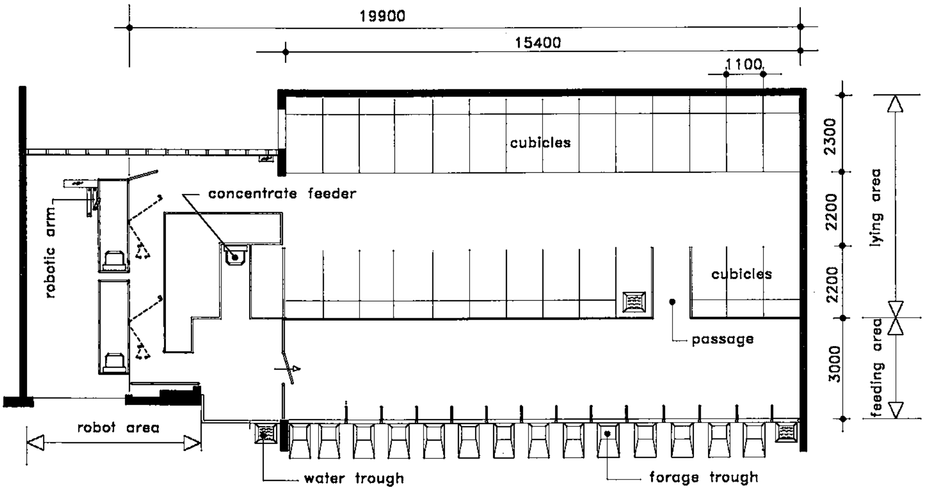

Figure 2: layout of the experimental barn in Duiven. Dimensions in mm (source IMAG-DLO)

Further we need one more, artificial, facility that we will call:

- Walking. The space in between the facilities is used for walking, idling or grouping. This takes nearly 25 percent of their time, so 5 to 6 hours a day. In that time they cover at most a few kilometers, so a better word for the facility might be `Standing.' Anyway, the walking area should be large enough to accommodate somewhat more than 25 percent of the herd.

3.2 The CQN model

The above description suggests a CQN model with 6 stations: 1. Milking robot,
2. Concentrate feeder,
3. Forage lane,
4. Water trough,
5. Cubicle and
6. Walking.

Walking is modelled as an infinite server. The other stations are single of multiple servers stations. In this CQN the customers are the cows. The number of cows is fixed and denoted by *H* (for herd).

3.3 The service times and visit frequencies

For the CQN model we need for each station the service time and the relative number of visits. This data is obtained from measurements in the experimental barn in Duiven. An extensive presentation and discussion of the measurements can be found in Halachmi at el.[2] We note, however, that the visit frequencies depend also on the layout. In Duiven part of the visits of the cows to the facilities Milking robot and Concentrate are not successful. The milking frequency is limited to once every 6 hours and they only receive concentrate after being milked. Figure 3 gives the frequency distribution of the service time in the Milking robot obtained from the measurements. The small service times, but also some of the very long service times correspond to unsuccessful visits of a cow to the robot. In the approximative analysis of the CQN model, however, we do not use the complete distribution of the service time. We only need its mean and standard deviation. The data we use is displayed in table 1. The sum of the visit frequencies is normalised to 1.

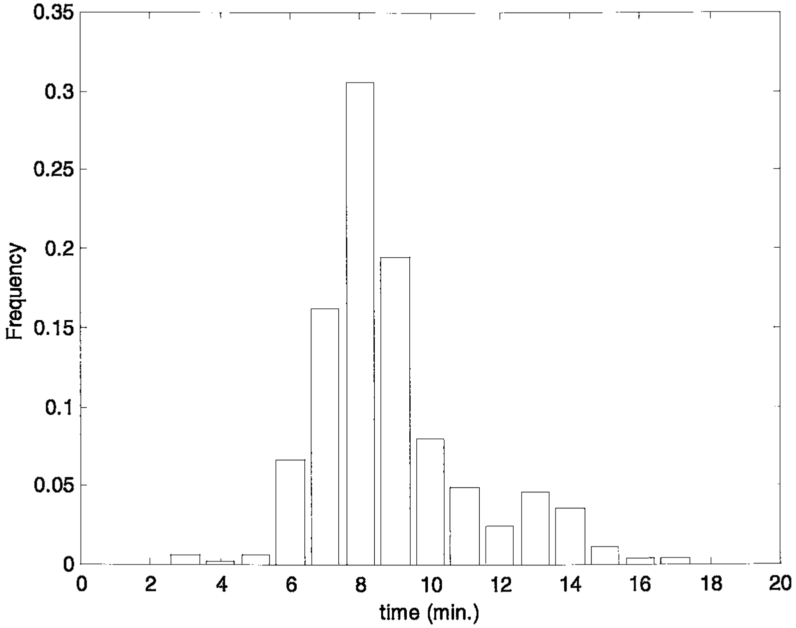

Figure 3: Frequency distribution of the service time (in min.) in the milking robot

Walking is modelled as an infinite server, so there is no waiting for Walking. Therefore it does not make any difference whether the time a cow spends in Walking consists of many short periods or a few longer ones. In the model we use this freedom to set the visit frequency for Walking equal to 1. From the measurements in Duiven we know that Walking takes 23.8 percent of the time[i]. So one 'visit' to Walking should take 23.8/(100-23.8) of the mean time needed for one visit to the other facilities (weighted with the visit frequencies). Since the herd in the barn in Duiven is small compared to the various capacities, cows rarely have to wait for service. So the mean time needed for one visit is equal to the mean service time. Hence, from the data in table 1 we obtain a mean walking time per visit of 5.36 minutes. In table 2 we show how according to the measurements a cow spends the time in the various facilities.

Table 1: Service requirements in the facilities in the barn

		Service time (in min.)	
Facility	Relative visit frequency	Mean	Standard deviation
Milking robot	0.164	8.41	2.52
Concentrate feeder	0.155	6.38	6.25
Forage lane	0.235	15.0	11.9
Water trough	0.170	3.18	2.30
Cubicle	0.276	38.9	60.3

Table 2: Percentages of time a cow spends in the various facilities

Facility	Percentage of time
Milking robot	6.1
Concentrate feeder	4.4
Forage lane	15.7
Water trough	2.4
Cubicle	47.7
Walking	23.8

3.4 The performance and design criteria

In a CQN we are normally interested in the mean waiting times and the means or distributions of the numbers of 'customers' or 'jobs' at the various stations. In our case that is not very different. Queueing is something cows do not like. In this respect they do not differ from humans. When a cow is waiting for a facility and another cow arrives, aggressive behaviour might occur. Particularly at the scarce facilities Milking robot and Concentrate waiting has to be limited. Some waiting for Cubicles is not really a problem because Walking seems to be an alternative for the Cubicles. So in the discussion about the design we will focus on mean waiting times and the queue lengths at the stations Milking robot and Concentrate feeder and on the maximum number of cows that can be accommodated in a certain design.

Given the visit frequencies, service times, capacities and herd size we can evaluate waiting times, queue lengths and utilisations for the various facilities. From these we can discuss and judge the design under consideration.

In the next section we present the algorithm for evaluating the performance.

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[i] The numbers determined from the data in Duiven are given in 3 digits. Of course, the measurements do not guarantee this accuracy.

4. The AMVA

A standard technique for the analysis of closed queuing networks is mean-value analysis (MVA[7,8]). The name MVA refers to the fact that it deals with relations between the quantities:

- mean time spent in a station,
- mean number of cows in a station, and
- mean number of visits per time unit to a station.

Exact MVA is based on Little's formula[9] and the arrival theorem[10] stating that in a CQN a customer moving from one station to another sees the network in equilibrium with one customer removed. Little's formula is valid under general circumstances, but the arrival theorem only holds exactly for product-form networks. The CQN model of the barn has no product-form solution, but we will adopt the arrival theorem as an approximation. We will denote this approximate MVA by AMVA.

Before formulating the AMVA relations we introduce some notation. The stations are numbered according to the list in subsection 3.2. The relative visit frequency to station *i* is v_i and the mean and standard deviation of the service time in station *i* are denoted by s_i and σ_i respectively. The mean residual service time R_i in station *i* upon an arrival instant is approximated by (see Ross[11])

$$R_i = \frac{s_i}{2}\left(1+(\frac{\sigma_i}{s_i})^2\right)$$

The number of servers in station *i* is c_i. We further introduce the following quantities depending on the herd size *H*,

$W_i(H)$	mean waiting time in station *i*,
$S_i(H)$	mean visit time in station *i* (waiting plus service time),
$\Lambda_i(H)$	mean number of visits per time unit to station *i*
$L_i(H)$	mean number of cows waiting (not in service) in station *i*
$\rho_i(H)$	server utilization in station *i*
$Q_i(H)$	probability that all servers are busy in station *i*.

We now formulate the relations for $W_i(H)$, $S_i(H)$, $\Lambda_i(H)$ and $L_i(H)$. The relation for $W_i(H)$ depends on whether station *i* is a single, multi or infinite server. In the infinite server station Walking (station 6) there is no waiting, so

$$W_6(H) = 0.$$

The other stations are single or multi server. In a single-server station we use

$$W_i(H) = \rho_i(H-1)R_i + L_i(H-1)s_i \qquad \text{(Eq.1)}$$

where

$$\rho_i(H-1) = \Lambda_i(H-1)s_i.$$

In a multi-server station the relation for the mean waiting time is a bit more complicated. If not all servers are busy the waiting time is zero. If all servers are busy and there are 0 or more jobs waiting then the new arrival first has to wait until the first departure and then it continues to wait for as many departures as there were jobs waiting upon arrival. As an approximation we assume that with c servers the time till the first departure and the time to clear the queue is c times smaller than with one server. So we use the approximation,

$$W_i(H) = Q_i(H-1)\frac{R_i}{c_i} + L_i(H-1)\frac{s_i}{c_i}. \qquad \text{(Eq.2)}$$

Clearly, for $H < c_i$ the probability $Q_i(H)$ is equal to 0. Otherwise it is approximated by the corresponding probability in an M/M/c_i system (see, e.g. Tijms[12]) with arrival rate $\Lambda_i(H)$ and mean service time s_i. So, for $H \geq c_i$,writing

$\rho_i(H) = \Lambda_i(H)\ s_i/c_i$, and

$$Q_i(H) = \frac{(c_i\rho_i(H))^{c_i}}{c_i!}\left\{(1-\rho_i(H))\sum_{k=0}^{c_i-1}\frac{(c_i\rho_i(H))^k}{k!} + \frac{(c_i\rho_i(H))^{c_i}}{c_i!}\right\}^{-1}.$$

Note that for $c_i = 1$ equation (2) reduces to the single server equation (1), and that for $c_i = \infty$ it simplifies to $W_i(H) = 0$. Equations (1) and (2) express the mean waiting time for herd size H in terms of quantities for herd size H-1. So they are recursive in H. We emphasize that the equations (1) and (2) for the mean waiting time are approximations, and that, of course, also other approximate equations are possible.

The mean visit time in station i is the sum of the mean waiting time and the mean service time, so

$$S_i(H) = W_i(H) + s_i.$$

To determine the arrival rates, i.e., the mean number of visits per time unit, $\Lambda_i(H)$ we first note that the mean time elapsing between the starts of two successive walks, $C(H)$ say, is equal to (recall that $v_6 = 1$)

$$C(H) = \sum_{i=1}^{6} v_i S_i(H),$$

since in between two walks a cow visits facility i on the average v_i times. Hence, the mean number of visits per time unit to facility i of one cow is $v_i / C(H)$. Since there are H cows around, we have

$$\Lambda_i(H) = \frac{v_i H}{C(H)} = \frac{v_i H}{\sum_{i=1}^{6} v_i S_i(H)}.$$

Finally, Little's formula applied to the queue in station i yields

$$L_i(H) = \Lambda_i(H) W_i(H).$$

This completes the set of AMVA relations. The relations can be solved recursively. Starting with an empty barn for which $L_i(0) = \Lambda_i(0) = 0$, we can subsequently compute the quantities $W_i(h)$, $S_i(h)$, $\Lambda_i(h)$, $Q_i(h)$ and $L_i(h)$ for $h = 1, \ldots, H$ using the relations formulated above. The AMVA algorithm is summarised below.

Step 1. *Initialisation*: $L_i(0) = Q_i(0) = 0$ *for all* i

Step 2. *For* h=1,2,...,H *compute for* i = 1,...,6

$$W_i(H) = Q_i(h-1)\frac{R_i}{c_i} + L_i(h-1)\frac{s_i}{c_i},$$

$$S_i(h) = W_i(h) + s_i,$$

$$\Lambda_i(h)=\frac{v_i h}{\sum_{i=1}^{6} v_i S_i(h)},$$
$$L_i(h)=\Lambda_i(h)W_i(h),$$
$$\rho_i(h)=\Lambda_i(h)\frac{S_i}{c_i},$$
$$Q_i(h)=0, \quad if\ h<c_i$$
$$=\frac{(c_i\rho_i(h))^{c_i}}{c_i!}\left\{(1-\rho_i(h))\sum_{k=0}^{c_i-1}\frac{(c_i\rho_i(h))^k}{k!}+\frac{(c_i\rho_i(h))^{c_i}}{c_i!}\right\}^{-1}, \quad if\ h\geq c_i$$

Based on $Q(H)$ and $L(H)$ we can compute an approximation for the queue length probabilities. Let $p(k,H)$ denote the probability of k cows (waiting or in service) in station i. For $k > c_i$ we set (as an approximation)

$$p_i(k,H)=(H-k+1)\alpha p_i(k-1,H)=\cdots=(H-c_i)_k\alpha^{k-c_i}p_i(c_i,H),$$

where $(n)_k = n(n-1)...(n-k+1)$. The factor $H - k + 1$ reflects the assumption that the arrival rate will be proportional to the number of cows that is not in station i. The two unknowns α and $p(c_i,H)$ are determined such that

$$\sum_{k=c_i}^{H} p_i(k,H)=Q_i(H), \qquad \sum_{k=c_i}^{H}(k-c_i)p_i(k,H)=L_i(H)$$

In the next section we will investigate the accuracy of AMVA.

5. Validation

We should verify that the CQN model is a reasonable representation of reality, and that AMVA produces good approximations for the performance of the CQN model.

A real life validation of the CQN model is complicated. The cows need a serious amount of time to adjust to a new layout and changes in the herd. Further, many other parameters, e.g., climate conditions or an occasional illness, influence the accuracy of the measurements. But we can say that the CQN model exactly describes the relative workloads of the facilities in the barn, and it takes into account the variability in the service times and the interference effects between the facilities. Further the performance of the CQN model has repeatedly passed the `face validation' test as several people familiar with the barn district found it accurately mimicking a real system.

To verify the accuracy of the AMVA we compare it with simulation of the CQN. The examples are based on the real barn measurements in Duiven. AMVA only needs the data in table 1, but the simulation uses more detailed information, i.e., the transition probabilities between the facilities and the frequency distributions of the service times. The walking times in the simulation model are taken to be exponential. In table 3 we list the performance of the Robot and Concentrate feeder for several scenarios. In each of the scenarios we have 12 eating positions at the forage lane, 3 water troughs and 27 cubicles. The accuracy of the simulation results is 0.1--0.5% for the utilization and 1--2% for the mean waiting time and mean queue length. The simulation time on a

SUN-5 170Mhz Workstation is for each scenario approximately 8 minutes. The computation time for AMVA is negligible.

The results in table 3 show that AMVA predicts the utilizations and hence the arrival rates perfectly. The predictions for the mean waiting times and mean queue lengths are good. For design purposes, we may conclude that AMVA is sufficiently accurate.

In table 4 we consider the approximation for the queue length probabilities, and compare it with simulation. We list $p_i(k,H)$,which is the probability that in station i all servers are busy and k or more cows are waiting for service.

The results show that AMVA produces good approximations. Clearly, the inaccuracy of the input data is more important than the inaccuracy of AMVA. In the next section we demonstrate how AMVA can be used as a practical design tool.

Table 3: Comparison of AMVA with simulation results

Scenario			Milking robot						Concentrate feeder					
			$\rho_1(H)$		$W_1(H)$		$L_1(H)$		$\rho_2(H)$		$W_2(H)$		$L_2(H)$	
c_1	c_2	H	amva	sim	amva	sim	amva	sim	amva	sim	amva	sim	amva	sim
1	1	10	.580	.578	4.26	4.41	.294	.303	.416	.418	3.48	2.81	.227	.184
2	1	10	.298	.296	.332	.344	.024	.024	.427	.428	3.58	3.50	.240	.235
		15	.434	.431	.833	.868	.086	.089	.623	.624	7.47	7.26	.729	.711
		20	.551	.548	1.60	1.65	.209	.216	.791	.793	14.4	14.0	1.78	1.74
2	2	20	.599	.595	1.89	1.97	.269	.278	.430	.431	1.17	.941	.157	.127
		25	.736	.731	3.60	3.83	.631	.666	.528	.530	1.99	1.54	.329	.256
		30	.858	.852	6.67	7.41	1.36	1.50	.615	.617	3.12	2.28	.601	.440
3	2	30	.594	.590	1.03	1.07	.217	.226	.639	.640	3.39	3.16	.678	.634
		35	.680	.677	1.69	1.76	.411	.426	.732	.734	5.35	4.95	1.23	1.14
		40	.757	.754	2.66	2.81	.719	.755	.814	.819	8.29	7.70	2.12	1.98
3	3	40	.789	.785	3.06	3.26	.861	.913	.566	.568	1.27	.956	.339	.256
		45	.868	.866	5.00	5.59	1.55	1.73	.623	.626	1.81	1.30	.530	.384
4	3	45	.668	.667	1.04	1.12	.331	.354	.638	.644	1.94	1.77	.583	.536
		50	.724	.726	1.54	1.73	.529	.599	.692	.701	2.71	2.55	.883	.841

6. Applications

A practical problem related to the design of a barn is for example the following. A farmer considering to buy additional milk quota wants to know whether the present capacity of the facilities is sufficient for holding a bigger herd. And if not, how much extra capacity is needed. Below we show how AMVA can be used in this situation.

We consider the barn described in section 3. The initial configuration is 1 milking robot, 1 concentrate feeder, 12 forage lane eating positions, 3 water troughs and 27 cubicles. The design criterion is an upper limit of 2 minutes for the mean waiting time in each facility. In table 5 we list for various herd sizes the minimal number of servers needed in each facility. This number is determined by using the following add-heuristic. We start with the initial configuration. If the mean waiting time in each facility is less than 2 minutes, we are done. Otherwise, we add one server to the facility with the greatest mean waiting time (i.e. the bottle-neck facility) and we repeat this procedure until the mean waiting time in each facility drops below the upper limit of 2 minutes.

Table 5 shows that many expensive robots are needed to keep the waiting times small. The reason is inefficient use of the robots. In the present layout each cow visits the robot nearly 10 times per day. A cow is milked 3 times a day. So the other 7 times, the cow occupies the robot, not because she has to be milked, but because she wants concentrate. Unsuccessful visits to the robot may be avoided by means of a selective gate in front of the robot, through which only cows may pass who have to milked. The effect of a selective gate on the required milking capacity can be evaluated with AMVA. It is not completely clear how this will alter the service times of the robot. We will assume that the service time of a successful visit to the robot has the same mean and standard deviation as in table 1. This is reasonable for its mean, but probably its standard deviation will be smaller (cf. subsection 3.3). We only have to reduce the visit frequencies to the Robot and the Concentrate feeder (since it can be reached only by passing through the Robot, see figure 1) with nearly 70 percent to 0.05 (see table 1). In table 6 we list for various herd sizes the minimal number of servers needed in each facility. The result is a substantial cost saving: for a herd of, e.g., 50 cows we now need 2 instead of 4 robots, and 2 instead of 4 feeders. On the other hand, some extra cubicles are required, but they are not expensive.

Table 4: Queue length probabilities for the Robot and Concentrate feeder

Scenario				$P_1(k, H)$				$P_1(k, H)$			
c_1	c_2	H	k	0	1	2	3	0	1	2	3
1	1	10	amva	.580	.206	.065	.018	.416	.155	.052	.015
			sim	.577	.223	.063	.014	.418	.135	.037	.009
2	1	10	amva	.137	.021	.003	.000	.427	.163	.055	.016
			sim	.124	.021	.002	.000	.428	.161	.053	.015
2	1	15	amva	.263	.066	.015	.003	.623	.361	.195	.098
			sim	.246	.070	.015	.003	.624	.358	.189	.093
2	1	20	amva	.392	.140	.047	.015	.791	.597	.431	.297
			sim	.373	.149	.049	.014	.793	.596	.424	.289
2	2	20	amva	.449	.174	.064	.022	.258	.101	.037	.013
			sim	.427	.185	.066	.020	.246	.088	.028	.008
2	2	25	amva	.624	.327	.164	.079	.364	.179	.084	.038
			sim	.602	.352	.179	.081	.350	.155	.063	.024
2	2	30	amva	.792	.528	.340	.211	.469	.274	.155	.085
			sim	.774	.576	.391	.245	.454	.237	.114	.052
3	2	30	amva	.347	.136	.052	.019	.498	.300	.174	.098
			sim	.320	.144	.055	.019	.493	.293	.166	.091
3	2	35	amva	.464	.224	.105	.047	.618	.432	.294	.194
			sim	.436	.235	.111	.048	.615	.424	.281	.180
3	2	40	amva	.578	.331	.184	.100	.730	.575	.443	.333
			sim	.553	.350	.201	.106	.730	.567	.427	.313
3	3	40	amva	.630	.376	.219	.124	.312	.167	.087	.044
			sim	.600	.400	.241	.135	.291	.141	.064	.028
3	3	45	amva	.762	.532	.364	.243	.384	.230	.134	.076
			sim	.741	.575	.417	.286	.364	.196	.100	.048
4	3	45	amva	.380	.180	.084	.038	.405	.247	.147	.085
			sim	.353	.192	.092	.040	.400	.238	.137	.076
4	3	50	amva	.467	.254	.135	.070	.481	.322	.212	.136
			sim	.453	.282	.161	.084	.484	.320	.206	.128

7. The Java applet Cow

The CQN model of the robotic barn has been implemented in a user-friendly Java applet called *Cow*. The performance of the barn can be easily evaluated with the applet. It offers several possibilities to show the results, i.e. in the form of bar charts, pie charts or simple text charts. The applet Cow can be used freely on the World Wide Web. The URL is: http://www.win.tue.nl/math/bs/stoch_opt/queueing_applets/cow.html

8. Conclusion

In this paper we presented a CQN model for a robotic barn. Since the CQN cannot be solved exactly, we used an AMVA. The computation time on a PC of AMVA is negligible and it produces good approximations. The CQN model provides a practical tool to support the design of robotic barns.

QN techniques are still uncommon in the analysis and design of livestock housing. As we demonstrated in the present study, these techniques appear to be very useful for design problems in this area as well.

Table 5: Minimal number of servers such that $W_i(H)\leq 2$ minutes for all i

						Robot		Concentrate		Cubicles	
H	c_1	c_2	c_3	c_4	c_5	$\rho_1(H)$	$W_1(H)$	$\rho_2(H)$	$W_2(H)$	$\rho_5(H)$	$W_5(H)$
10	2	2	12	3	27	.305	.345	.219	.240	.176	.000
20	2	2	12	3	27	.599	1.89	.430	1.17	.345	.000
30	3	3	12	3	27	.605	1.08	.434	.531	.523	.003
40	4	3	12	3	27	.602	.668	.575	1.33	.694	.191
50	4	4	12	3	28	.738	1.64	.529	.596	.821	1.43
60	5	4	12	3	32	.701	.957	.628	1.19	.852	1.89

Table 6: Minimal number of servers such that $W_i(H)\leq 2$ minutes for all i in a barn with a selective gate

						Robot		Concentrate		Cubicles	
H	c_1	c_2	c_3	c_4	c_5	$\rho_1(H)$	$W_1(H)$	$\rho_2(H)$	$W_2(H)$	$\rho_5(H)$	$W_5(H)$
10	1	1	12	3	27	.200	.980	.152	.971	.189	.000
20	2	2	12	3	27	.201	.169	.152	.132	.380	.000
30	2	2	12	3	27	.301	.412	.228	.314	.569	.011
40	2	2	12	3	27	.398	.788	.302	.583	.752	.487
50	2	2	12	3	30	.489	1.32	.371	.938	.832	1.40
60	3	2	12	3	35	.387	.305	.440	1.42	.846	1.42

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Chapter 3

Applying the queuing network model

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Abstract

The design of various conventional dairy barns is based on centuries of experience, but there is hardly any experience with robotic milking barns (RMB). Furthermore, as each farmer has his own management practices, the optimal layout is 'site-dependent'. A new universally applicable design methodology has been developed to overcome this lack of experience with RMB and to be able to design the optimal layout for RMB. This model for optimising facility allocating, based on cow behaviour, welfare needs, and facility utilization, uses queuing network theory, Markov process, and heuristic optimization. The methodology has been programmed into a software application, supporting the design process. On a given farm presented below as a case study, numerical results include:

If the herd contains more than 50 cows, the forage-lane utilisation is greater than 70% (or idle-time is less than 30%). To meet animal-welfare demands, the herd size should not exceed 60 cows. Therefore, the herd should comprise 50-60 cows.

In the second scenario examined, the average robot idle time was 25 %, queue length was 3 cows, and each cow waited for about 3 min at the robot.

It is still uncommon to apply techniques from queuing-network theory to livestock housing. This study demonstrate their potential as practical design tools that meet both economic and animal welfare needs.

1. Introduction

Robotic milking is relatively new. It affects factors such as cow behaviour, farm routine, feeding procedures, and management practices that determine the barn layout. The design of milking-parlour oriented barns is based on decades of experience, but there is no such experience with robotic barns. Furthermore, the optimal layout is 'site-dependent', because each farmer has his own management attitude, feeding routine, preferred cow-traffic, existing facilities, and many more individual characteristics. In order to overcome this lack of experience and to be able to design an optimal layout, suitable for any farmer or site - a novel approach to planning is needed.

Halachmi et al.[1] concluded that under certain conditions the voluntary visits to the milking robot even out facility usage throughout day and night to a continuous-time stochastic process. They quantified this process in terms of theoretical Probability Distributions (PD), which opens up the opportunity to treat a barn as a queuing network, and to design the barn by using queuing models.

A previous paper[2] described the development of a closed queuing network model for RMB, to evaluate performance criteria, such as queue length, waiting time and facility utilization. In order to facilitate these performances into a practical design tool, the first step is to analyse cow 'flow' between barn facilities, using Markov process (section 3.1). It is assumed that each facility acts as a stochastically independent unit. Consequently, each facility is analysed separately, using queuing theory (section 3.2). Section 3.3 develops an 'aspiration-level' model, and provides an analysis of the overall performance of the barn. Section 4 lists the validation steps.

This study is part of a research project whose goal is to develop a designing tool for optimal RMB, based on cow welfare needs and facility utilization. The queuing model appears to be a practical tool. In section 6, tables, figures, and Graphical User Interface (GUI) are used to explain the design tool and its scope in a given practical situation.

2. Literature review

At the end of 1997 around 175 milking robots were in use on commercial Dutch farms, and more are expected to be introduced each year (Rossing *et al.*[3]). Robotic milking increases milking frequency, which reduces the stress on the udders of high-yielding cows, and increases the milk yield; it also reduces mental and physical labour. If the cows choose to be milked more frequently than twice daily, we would expect an increase of up to 15% in milk yield (Hillerton and Winter[4]), whereas attendance less than twice per day would reduce milk yield and might increase the incidence of mastitis (Wilde and Peaker[5]). However, the motivation to be milked is relatively weak (Prescott *et al.*[6]). In a conventional barn, the milker brings the cows to a waiting area from where they are forced to enter the milking parlour. In a milking robot situation, cows are expected to visit a milking stall voluntarily. The barn layout (facility allocation, location, and preventing bottlenecks) affects robot attractiveness and the cows' visiting frequency. It is therefore crucial to plan the layout carefully[7-16]. Other facilities that have to be included in the design of the RMB in addition to the milking robot stalls are the Concentrate Self-Feeder[17] (CSF), forage-lane-eating positions[18,19], water troughs[20,21,22], and cubicles [23,24]. Traditional ratios of these facilities established for a milking-parlour barn[25] are usually, one cubicle per one cow, one forage lane-position per one cow, and one CSF per 20-25 cows. But, it has already been verified that under certain conditions, it is possible to accommodate more cows than cubicles or feeding stands without major problems[26,27]. However, since robotic milking is so new, the experience in designing RMB is yet virtually none. The ratios of facilities per head have to be calculated for RMB.

In the 60s, queuing theory was found to be an effective tool to study the performance of complex communication systems, networks, resource allocation, logistics, and complicated interconnections in a system. Thousands of research papers, formulating and analysing queuing models, have already appeared in the literature, and many more are being published each year (Van Beek[28], Kleinrock[29]). So far, however, queuing theory has not been used to design barns.

Notations and Abbreviations

α	aspiration level for waiting time in queue, min.;
β	aspiration level for queue length, number of cows;
γ	aspiration level for idle time rate;
λ_I	arrival rate to facility i, adjusted to the herd size, cows/min;
μ_i	service rate at busy server in facility i, cows/min;
π_i	limiting probabilities, the proportion of transitions that take the cows into the facility i;
ρ_i	utilisation factor or $(1-\rho_i)$ = Idle time factor;
c_i	number of parallel servers, facility positions in a facility i;
H	herd size, number of cows in the barn;
i,j	indices, facilities in the barn: (1) concentrate self–feeder; (2) forage lane; (3) water troughs; (4) cubicles; (5) milking-robot; (6) the virtual 'walking';
k	engineering safety factor;
L_i	queue length in facility i, cows;
n_{ij}	number of movements of cows from facility i to facility j;
P_{ij}	transition probability of moving from facility i to facility j;
q_i	stable (steady-state) probability distribution of finding a cow in specific facility i;
s_i	mean service time in station i, min.;
W_i	waiting time in queue station i for each individual customer, min.;
AMVA	approximated mean value algorithm (equations are given by Halachmi et al[2]);
CSF	computerised concentrate self–feeder;
GUI	graphic user Interface;
PD	probability distribution;

3. Material and methods

3.1 Interactions between barn facilities and cows

The cows determine how the use of the various facilities is linked, after having been serviced in facility *i*, the cow proceeds to facility *j*. The transition probabilities P_{ij}, based on a discrete time Markov chain (Hillier and Lieberman[30]), can be calculated:

$$P_{ij} = \frac{n_{ij}}{\sum_j n_{ij}}, \quad i,j = 1,\ldots,6 \qquad (1),$$

where n_{ij} denotes the number of movements from facility i to j measured by Halachmi *et al.*[1], and $\sum_j n_{ij}$ is the total number of movements from *i*. The transition probabilities Pij is shown in table 1.

The limiting probability π_i, the proportion of transitions that take the cows into the facility i, is the unique non-negative solution of

$$\begin{cases} \pi_i = \sum_{j=1}^{6} \pi_j P_{ji}, \quad i = 1,\ldots,6 \\ \sum_{i=1}^{6} \pi_i = 1 \end{cases} \qquad (2). \qquad\qquad q_i = \frac{\pi_i s_i}{\sum_j \pi_j s_j} \qquad (3).$$

Based on continuous-time Markov process (*e.g.* Grimmett and Stirzaker[31]; Ross[32]), and the mean service time (s_i) at the various facilities, the *Stable* (steady-state) *probability distribution* (q_i) gives the fraction of the time that a cow is expected to spend in each of the six facilities.

The experiment[1] was carried out with unlimited availability of facilities for the cows (significantly, more cows than facilities); no queue or pressure on a facility had ever happened during the experiment. Therefore, the service time (s_i, acquired by this experiment) is an upper estimate, which satisfies the animal's welfare needs, independently of the herd size (H) or barn layout. It does not imply that the process settles down into one state; on the contrary, the cows continue to make transitions from facility to facility.

In structural-engineering, 'safety-factor', $k > 1$ is frequently used, so therefore the hypothetically optimum number of servers (c_i*) can be expressed as:

$$c_i^* = k\, q_i\, H,\ i=1,\dots,5 \qquad (4).$$

For example, a farmer has 100 cows, and given k=1.2, then, based on *Fig.* 1, the optimal number of cubicles is 1.2x0.61x100≅74, and the optimal number of forage-lane positions is 1.2x0.13x100≅16 (facility allocation is rounded up). But, Eq 4 has two drawbacks.

The utilisation levels (ρ_i) become the same for all the facilities in the barn. This means that an expensive facility and a relatively cheap one are treated the same (for instance, a milking robot might cost half million NLG, while a water trough costs only a few hundred NLG). The numbers of facilities are integer and the vector q has real values. For example, 2.2 robots would not be practicable, and either '2' or '3' must be chosen.

The 'aspiration-level model' and 'queuing model' (outlined below), combined with graphical user interface (GUI) overcome these drawbacks and give the designer additional freedom in fine-tuning the facilities allocation while remaining near the balanced design dictated by the stable distribution.

3.2 Using a queuing network model to evaluate barn performance

The barn is actually a queuing network, i.e., it contains a series of service facilities ('stations'), at some or all of which, cows must receive service; for example, consumption of concentrate, forage and water are physiologically linked. It is therefore necessary to study the entire network (the barn). *Fig.*2 outlines the network model of robotic milking barn. It can be seen that cows prefer to remain in the cubicles longer (59.42 min) than at the other facilities.

Some of our underlying PDs are of a general type[1], therefore, an exact analysis of our network is impossible (Baskett *et al.*[33]; Lemoine[34]; van Vliet[35]). We therefore have to rely on methods that approximate the behaviour of the network. For practical purposes, statistics such as mean queue length, waiting times and utilization are needed. The so-called Approximated-Mean-Value Analysis (AMVA) given by Halachmi *et al.*[2] provides the desired statistics, and establishes the basis for heuristic extension.

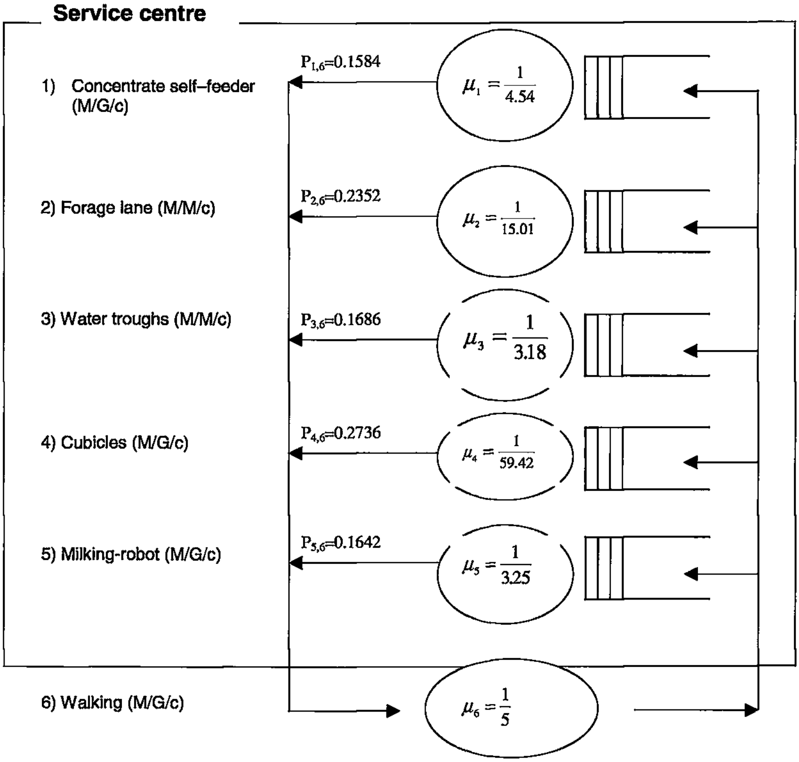


Fig. 1. Network model of robotic milking barn;

Note: the notation *M/M/c* indicates a queuing process with exponential interarrival times, exponential service time, and *c* parallel servers; *M/G/c*, exponential interarrival times, general distribution service time, and *c* parallel servers[36]. the service rates (μ_i), and transition probabilities (Pij) were measured by Halachmi et al.,[1]

3.3 Aspiration level

As the level of service increases (more places for feeding, drinking, milking, *etc.*), the cost of the barn increases, in contrast to the 'cost' of cows waiting, which decreases. The optimum service level occurs when the sum of the two costs is minimal. However, it is difficult to determine the 'cost' of cows' waiting time. Therefore, we must seek other criteria for making design decisions. One possible design criterion could be restricting the average waiting time at a given facility to 2 min per cow. This type of decision model is based on the use of an *aspiration level* that the service facility must satisfy. The farmer, designer or researcher can set the aspiration level according to specific farm conditions. An aspiration-level model recognises the difficulty of estimating cost parameters and therefore, is a more straightforward analysis, making direct use of the operating characteristics of the barn. 'Optimal' is seen in the sense of satisfying certain aspiration levels set by the decision-maker. These aspiration levels are defined as upper limiting values of the conflicting performance measures that the decision-maker wishes to balance.

Let the design criteria be the aspiration-levels for waiting time (W_i), queue length (L_i) and facility idle time ($1-\rho_i$). The optimum is the minimum number of servers, which satisfies the aspiration-level constraints (α_i, β_i and γ_i). The solution can be determined for each facility-i separately. W_i and L_i are monotonically decreasing functions and ($1-\rho_i$) is a monotonically increasing function of c_i , and since only an integer solution has physical meaning, the optimum is determined visually by plotting W, L and ($1-\rho$) against H. By drawing α, β and γ on the graph, the optimum integer (c^*_i) that satisfies all constraints (aspiration-levels) can be determined. Naturally, if these conditions cannot be satisfied simultaneously, it is necessary to relax one or more restrictions before a decision can be made.

4. Verification and Validation

The model is based on well proven mathematical equations, a number of steps were taken to either verify that the model works as intended and to validate that its operation is a reasonable representation of reality.

1) The model was compared with real barn measurements (*Fig.* 3). It was found that the model prediction fited the empirical data,
2) The model passed a 'face validation' test as several people familiar with the barn found the model's behaviour mimicking that of real system,
3) The model was subjected to 'extreme condition' tests, such as setting herd size to extremely high levels. Under such conditions, the simulation's behaviour was still reasonable,
4) Several consistency checks were performed, such as making incremental increases to herd size (no. of cows) and seeing that they led to reasonable and steadily increasing values for the average waiting time required to enter the facility,

Our working assumptions derived from literature survey are the following:

- It is the modeller's responsibility to ensure that the PD employed fits the intended barn. The best source of validation information is the farm records
- It may be possible to test parts of the model against part of an existing system on the same farm.

5. Results and applications

This study implements the mathematical algorithm into a practical design-tool. By visual analysis of the barn performance, the designer can judge whether or not the layout fits the cows' needs for facility allocations. Special care was taken to produce a user-friendly GUI.

One of the practical problems related to this theory is that of a farmer wanting to determine the number of positions needed for his actual herd and the distribution among the various facilities. Alternatively, the farmer might have a given total number of facilities installed in the barn and would like to determine the herd size for optimal utilization. Since the possibilities of interactive creative design are numerous, even for a single farm, only a few typical cases were chosen. The following tables and graphs are used to explain the algorithm and demonstrate its scope in a given practical situation.

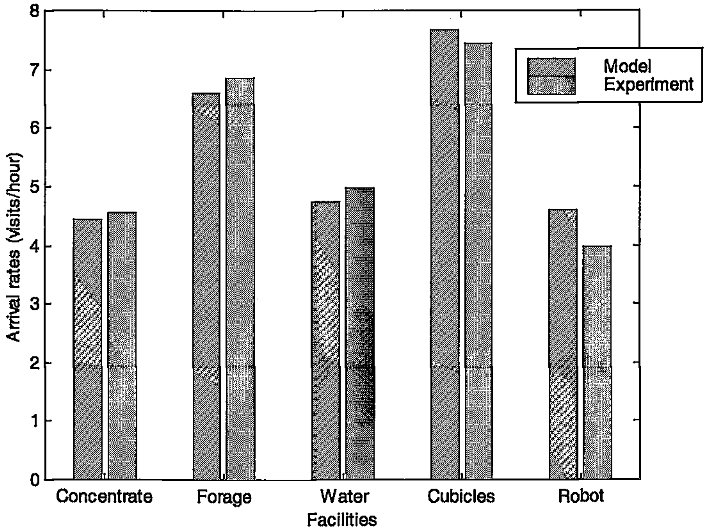


Fig 2 . Arrival rates: predicted and measured

5.1. Transitions of the cows among the barn facilities

Table 1 presents transition probabilities of the cows between the barn facilities. It can be seen that cows' popular movements appear to be between Forage-lane and Cubicles and between Forage-lane and Water troughs. If a 'forced routine' preventing these movements is applied, the cows will suffer certain stress. It can be seen that in 90 % of the cases, a CSF visit follows a robot visit. This suggests that the main reason for going through the robot is the desire to get concentrates, and suggests that CSF, either in the milking stall or standalone, is an effective way to force routing. It can be seen that the frequency of transition of a state to itself is not zero, since a state can be succeeded by itself. For example a cow can leave a water trough and move to another one or even return to the original trough after a few minutes without visiting any other facility. Adding the 'walking' facility ensures (artificially) that the frequency of the transition of a state to itself is zero; in fact, all transitions are to or from the 'walking facility' (*Fig.* 2 includes 'walking').

Table 1: Transition probabilities (matrix) between facilities in the barn

Departure facility (from...)		Probabilities of movement to barn facilities (to...)				
		Concentrate (1)	Forage (2)	Water (3)	Cubicles (4)	Milking (5)
Concentrate	(1)	0.03	0.62	0.11	0.24	0
Forage	(2)	0	0.03	0.16	0.79	0.01
Water	(3)	0.02	0.45	0.10	0.15	0.28
Cubicles	(4)	0	0.16	0.35	0.08	0.41
Milking	(5)	0.90	0.05	0.01	0.03	0.01

The stable probability distribution (q_i, Fig 1) can be interpreted as follows: if the barn is observed after a sufficiently long time (after the influence of the initial state of the system has diminished), the probability of finding a randomly selected cow in facility i is given by q. And, q_i presents the mutual interactions among the facilities, imposed by using a milking robot. Therefore, q_i appears to be the fractions of the facility usage that should ideally be allocated to satisfy the cow's behaviour pattern and animal's welfare needs.

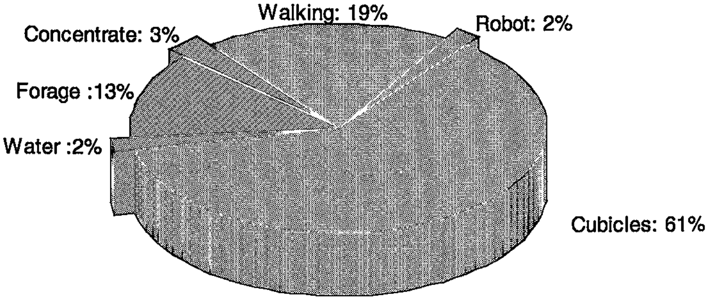


Fig. 3 . Stable probability distribution (q_i, %)

5.2. Determining the design starting point

The target was a 60 cow herd. The initial point was the barn configuration described by Halachmi *et al.*[1] (with 10 cows). Table 2 predicts what will happen if the number of cows is increased and it shows how we can tune the system by adding servers as needed. It can be seen that the starting configuration (one CSF, 12 forage lane positions, 3 water troughs, 27 cubicles, and two milking-robot stalls) may hold up-to 25 cows. After that, the utilization of the *CSF* is rather intense (77%) which results in a long queue (2.5 cows) and waiting time (15 min). Adding one *CSF* last up to 40 cows, in that case the bottleneck appears to be the number of cubicles and the CSF. Adding 23 cubicles (to make it 50) and 1 CSF (to make it 3) gives optimum balanced performance of all the facilities, satisfies aspiration level (short queue: less than two cows are waiting, less than 3 min waiting time), and minimises costs (facility utilization is intense: 68%, 83%, 92%, and 75%).

5.3. The design process

The next step along the design process is to use the GUI to fine-tune the optimal number of servers for each facility separately. Consider the forage lane. First, the farmer has to specify his aspiration levels for queue length, waiting time, and utilization for each individual facility. *e.g.*, queue length: 'up to one cow is waiting' ($\beta=1_{\text{cows}}$), waiting time: 'less than 1½ minutes' ($\alpha=1½_{\text{min.}}$), and utilization level: above 70% (i.e. idle-time less than 30%, γ=0.3). In *Fig. 4*, forage-lane performance against herd size, a fixed number of forage lane positions (12), and aspiration-levels are shown. On one hand, if the herd contains more than 50 cows, the utilization ≥

70% (or idle-time ≤ 30%). On the other hand, to meet animal-welfare aspiration levels (α and β), the herd size should not exceed 60 cows. In order to meet all aspiration levels, the herd should comprise 50-60 cows. Therefore, if the cowshed is built on a 1:5 ratio, *e.g.*,12 forage yoke gates for 60 cows, the average queue length is expected to be one cow and the expected waiting time is 1½ min. To express concern with animal welfare, it is recommended to build on a 1:4 ratio (48 cows), which gives a rather short queue (theoretically, ¼ cow waiting ⅓ min.). Either case would be more economical than the existing situation, 1:1 ratio in traditional farm with milking parlour. It can be seen (*Fig. 5*) that 52 cubicles are needed in order to meet the same aspiration levels for 60 cows.

Table 2: The design process, utilisation (ρ), waiting time (*W*) and queue length (*L*)

	CSF (1 feeding positions)			Forage (12 positions)			Cubicles (27 positions)			Robot (2 stall)		
H (cows)	ρ	W (min.)	L (cows)	ρ	W	L	ρ	W	L	ρ	W	L
10	0.34	2.69	0.20	0.14	0.00	0.00	0.28	0.00	0.00	0.12	0.03	0.00
15	0.50	5.19	0.57	0.20	0.00	0.00	0.41	0.00	0.00	0.18	0.08	0.01
20	0.64	9.01	1.27	0.26	0.00	0.00	0.54	0.00	0.00	0.24	0.14	0.02
25	0.77	15.05	2.55	0.31	0.00	0.00	0.64	0.00	0.00	0.29	0.21	0.04
	CSF(2 feeding positions)			Forage(12)			Cubicles(27)			Robot(2)		
cows	ρ	W	L	ρ	W	L	ρ	W	L	ρ	W	L
25	0.42	1.23	0.23	0.35	0.00	0.00	0.71	0.00	0.00	0.31	0.25	0.05
30	0.50	1.90	0.42	0.41	0.01	0.00	0.84	1.00	0.38	0.37	0.38	0.09
35	0.56	2.62	0.64	0.45	0.02	0.01	0.93	4.44	1.87	0.41	0.50	0.13
40	0.58	3.21	0.83	0.48	0.03	0.01	0.98	11.13	4.95	0.43	0.58	0.16
	CSF(3 feeding positions)			Forage(12)			Cubicles(50)			Robot(2)		
cows	ρ	W	L	ρ	W	L	ρ	W	L	ρ	W	L
40	0.45	0.66	0.20	0.55	0.07	0.03	0.61	0.00	0.00	0.50	0.78	0.24
50	0.56	1.31	0.48	0.68	0.36	0.20	0.76	0.00	0.00	0.62	1.42	0.54
60	0.65	2.26	0.96	0.79	1.16	0.73	0.88	0.96	0.70	0.72	2.38	1.05
65	0.68	2.80	1.25	0.83	1.82	1.21	0.92	2.28	1.77	0.75	2.96	1.38

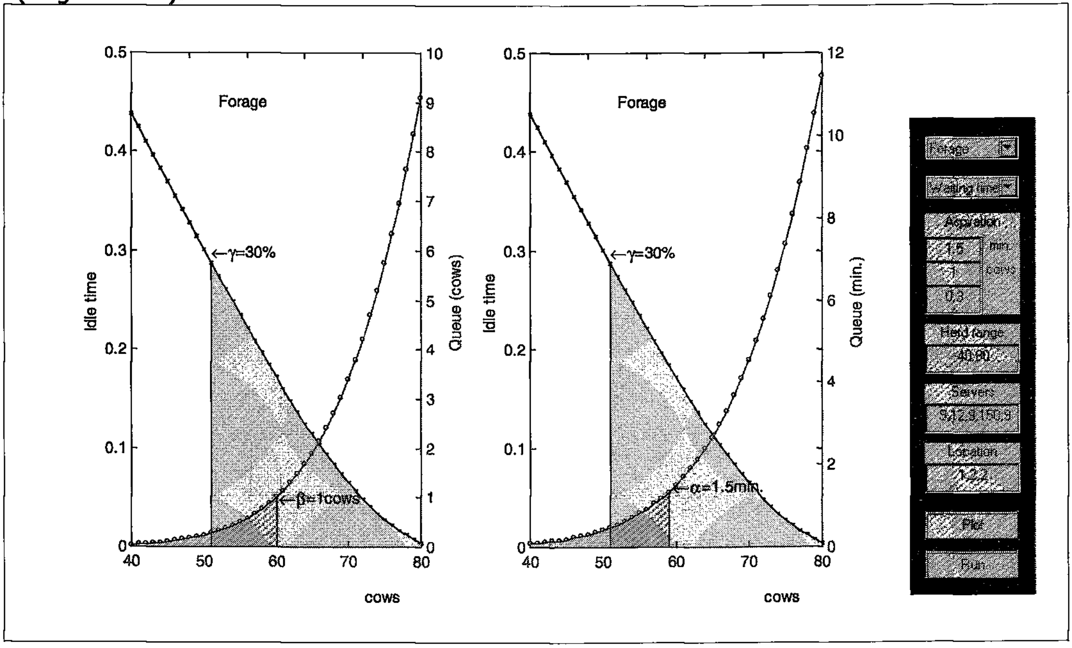
CSF, computerised concentrate self–feeder; *H*, herd size, number of cows in the barn; ρ, utilisation (or, $1\text{-}\rho$ is idle time) rate; *W*, waiting time in the queue for each individual cow, *min.*; *L*, queue length, *cows*;

5.4. The graphical user interface (GUI)

The GUI enables the optimal decision to be obtained simply by 'mouse-clicking'. For example see *Fig*.4, where by clicking the upper button the 'Forage' (*Fig*.4) was changed to 'Cubicles' (*Fig*.5) – the facility performance presented was changed, possibly changing the other parameter values on the computer screen. The iterative design and analysis described above can be repeated on all the facilities in the barn, until an 'optimal design' has been achieved.

The third button ('Location') determines the location and the size of a graph displayed on the screen, enabling visual-analysis while comparing few facilities on single computer screen. The combining of all the facilities in the barn into one network model, and displaying on a single screen prevents a 'bottleneck'. In order to do so, the designer should compare the working load (utilization and queue) between facilities.

Fig.6 shows the interactive capacity of the GUI, regarding overall performances of a barn, displayed on a single screen. As a second example, we assume that a designer has a herd size, H of 140 cows and wants to vary the number of servers. It can be seen that, if the configuration (the fourth button) is 6 conc., 27 forage lane positions, 115 cubicles, and 4 milking robot stalls, then with up to 130 cows the queue is moderate, but once herd size exceeds 140 cows the queue for the cubicles increases sharply. Since the costs of the robot are relatively high, its aspiration-levels have been slightly adjusted: idle time = 25 %, queue is 3 cows are waiting 3 min (instead of 30%, 1 cow, 1½ min.). It can be seen that given these aspiration-levels, barn configuration accommodates up to 140 cows, and less than 120 cows results in inefficient use of the facilities (long idle-time).



Aspiration: 1.5 min.; 1 cows; 0.3

Herd range: 40:80

Servers: 5,12,9,150,9

Location: 1,2,2

Fig 4 . Forage lane performance and aspiration-levels as a function of the number of cows (40-80) using a fixed number of forage lane positions (12). The system performance measures are waiting time, queue length (right-side Y-axis), and idle time as ratio (left-side Y-axis). The aspiration-levels are $\alpha=1½$ min, $\beta=1$ cows and $\gamma=30\%$

Water troughs (9 units) were taken into account. But since they have no influence on the queue (low utilization, ρ = 0.38 for 140 cows, and W = L ≈ 0) and relatively low installation and operation costs, they were suppressed from this computer screen in order to keep it simple, and allow more interesting facilities be presented.

The following utilisation (ρ) summarise the 'balanced design' that has been achieved, (herd size is 140 cows): ρ_{Conc}=0.77; ρ_{Forage}=0.84; ρ_{Water}=0.38; $\rho_{Cubicles}$=0.90; ρ_{Robot}=0.85. The average queue lengths are, L_{Conc}=1.88; L_{Forage}=0.83; L_{Water}=0.00; $L_{Cubicles}$=0.80; L_{Robot}=2.59 cows. The design process has been completed.

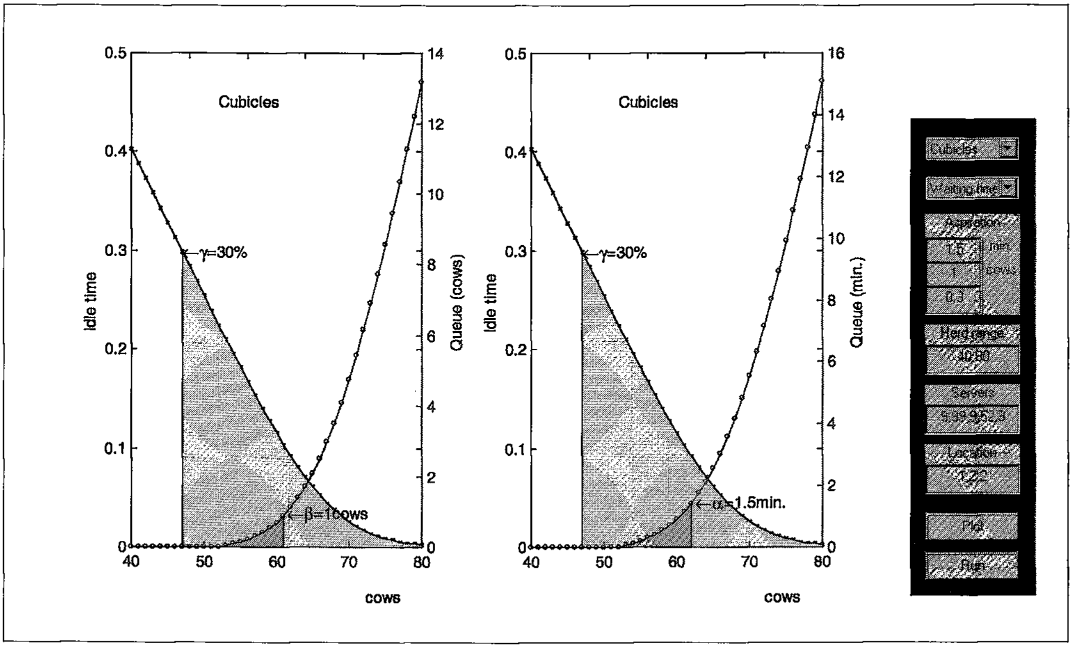


Fig 5. Cubicles performance and aspiration-levels as a function of the number of cows (40-80) using fixed number of cubicles (52). The system performance measures are waiting time, queue length and idle time. The aspiration-levels are $\alpha=1\frac{1}{2}$ min, $\beta=1$ cows and $\gamma=30\%$

6. Discussion

It is common-knowledge that a cow spends most of her time in the cubicle area, less time in the forage lane, *etc.*, but q expresses the exact ratio between the facilities, an important piece of information in itself, which is also in agreement with the observation by Uetake *et al.*[37].

In the present version of the model, all cows are treated the same. This means that the waiting times for dominant and low-ranking cows are equal, which is obviously a simplification. Cows' behaviour shows the effects of social rank; *e.g.*, lower-ranking cows spend longer in the waiting area, in-front of the robot (Ketelaar-de Lauwere *et al.*[38]). Queuing theory provides an additional feature: the 'priority queue', which make it possible, in the future, to incorporate the impact of social rank into the model.

The conclusions from this queuing model are valid only if the steady-state condition is properly maintained. For example, if forage is offered once or twice a day instead of continuously, this stochastic steady-state model would no longer hold. A field experiment has shown that a steady-state can be achieved in the barn (Halachmi *et al.*[1]). Increasing the herd size may increase the time necessary to reach social stability (Kondo and Hurnik[39]), and competition for resources such as water, feed or resting space also has a pronounced effect on this time, as does the group composition, age, and social experience of the animals. But we assume that a sufficiently long time had elapsed from the moment of assembling the cows into a herd, so a given group can be considered to be socially stabilised.

The next steps could be simulations and economic optimization. It would be possible, if the queue cost of the cows could be quantified in terms of performance, and by attaching cost values to the aspiration-level model.

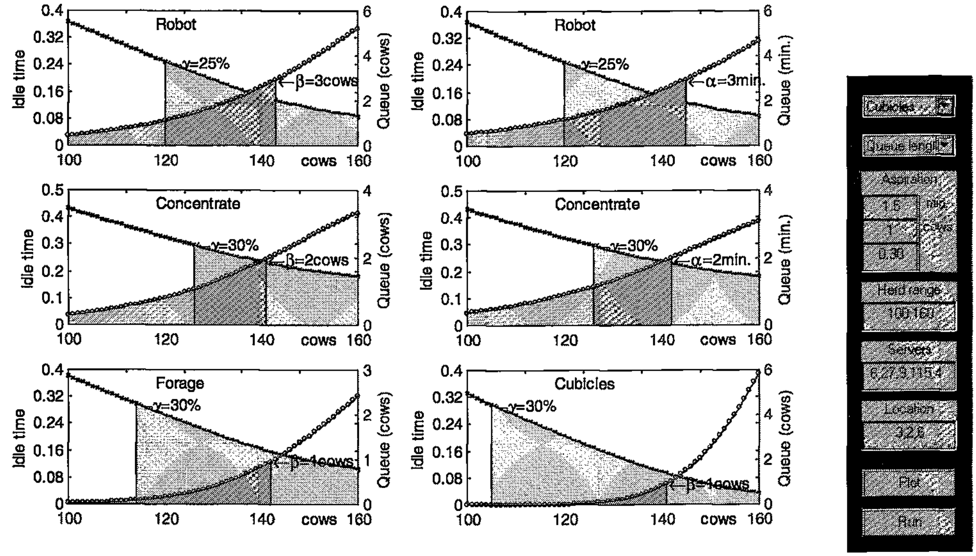


Fig 6 . Performance of the entire barn: 6 concentrate feeders, 27 forage lane positions, 115 cubicles, and 4 milking robot stalls as function of number of cows (100-160). The system performance measures are waiting time, queue length and idle time. The Robot's aspiration-levels are α=3 min, β=3 cows, γ=25%, elsewhere, α=1½ min, β=1 cows and γ=30%

7. Conclusion

This study has contributed towards a designing tool, based on cow behaviour, cow welfare needs, queuing theory, Markov process and heuristic optimization. The tool enables an RMB designer to optimise the facilities allocation in the barn by specifying 'aspiration levels' (queue length, waiting time, and facility utilisation). It appears to be a practical tool for evaluating the performance of configuration of facilities, the entire network, or each facility separately. Visual analysis of the barn performance enable the designer to judge whether the layout meets the cows' needs for facilities allocation. Special care has been taken to produce a user-friendly GUI.

Numerical conclusions:

1) The transition probability matrix shows that in 90% of the cases, a CSF visit follows a robot visit. This suggests that the main reason for going through the robot is to get concentrates. Therefore CSF is an effective way to force 'traffic routine' (either stand-alone or in the milking stall). Widespread movements appear to be between Forage-lane and Cubicles and between Forage-lane and Water troughs. If a forced routine prevents these movements, the cows may suffer some stress.

The possibilities of interactive creative design are numerous, even for a single farm; therefore only two simple cases were selected:

2) On the particular farm, presented above (β=1 cows, α=1½ min, utilization over 70%, 1 CSF, 12, forage position,..., *etc.*), the following conclusions were reached: If the herd is larger than 50 cows; the forage lane utilization ≥ 70% (or idle-time ≤ 30%). And, to meet animal-welfare aspiration levels (α and β), the herd size should not exceed 60 cows. Therefore, the herd should comprise 50-60 cows.
3) On the second farm, presented above, the following conclusions were reached. A barn configuration of 6 CSF, 27 forage lane positions, 115 cubicles, and 4 milking robot stalls, is enough for up to 140 cows, and fewer than 120 cows results in inefficient usage of the facilities (long idle-time). Average robot's idle time = 25 %, queue length = 3 waiting cows, each cows waits about 3 min.

Network techniques for the analysis and design of livestock housing are still uncommon. This study demonstrates, however, that techniques can be useful for designing to meet both economic and animal welfare needs.

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Chapter 4

Developing a behaviour-based simulation model

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Paper name:

Designing the optimal robotic milking barn, part 3: behaviour-based simulation

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Abstract

Robotic milking affects factors that determine the barn layout, such as cow behaviour, farm routine, feeding procedure and management practices. As there is hardly any experience with robotic barns, and each farmer has his own management attitude, depending on his personality and local conditions, the optimal layout, therefore, varies per case. A new integrated design approach is needed, in order to overcome lack of experience and to be able to design the optimal layout for the Robotic Milking Barn (RMB) suitable for any farmer or site. A behaviour-based simulation model, which enables a designer to optimise facility allocation in a barn, has been developed as a design tool.

The proposed approach overcomes difficulties characterising RMB design. Simulation experiments allow equipment and layouts to be evaluated jointly, an initial design can be fine-tuned to produce a balanced system (an 'optimal layout'), specific to the farm in question, within a reasonable time. Executing the suggested methodology, step by step, an optimal RMB has been designed, meeting both economic and animal welfare needs. If a simulation study had not been performed and if a bottleneck in the cow-traffic had been discovered after installation, the cost of retrofitting extra capacity could have been significant. On the basis of simulation results for the farm presented as a case study, significant design conclusions were reached.

1. Introduction

Robotic milking is a recent development that affects factors such as cow behaviour, farm routine, feeding procedures, and management practices that need to be taken into account when designing barn layout. Whereas in a conventional barn the milker brings the cows to a waiting area from where they have to enter the milking parlour, in a RMB a cow is expected to visit a milking stall voluntarily several times per day in response to her biological clock. As the barn layout strongly influences the cows' arrivals at the milking robot, it must be carefully planned.

Whereas the conventional dairy barn is based on decades of experience, there is hardly any experience with the RMB. Furthermore, there is wide variety between farms; each farm has individual characteristics such as ventilation and existing facilities, and each farmer has his own feeding routine, management attitude, preferred cow-traffic, etc. The optimal layout, therefore varies per case. A new integrated approach to planning is needed, in order to overcome the lack of experience and to be able to design an optimal layout, with a universally applicable technique, suitable for any farmer or site,

The mechanical designs of the milking robot itself, of the Concentrate Self-Feeder (CSF), the yoke gates, and the cubicles, should be comfortable to the animals. The present paper assumes that these items have been developed by commercial companies, and their characteristics and capability are known, i.e. either by the producer or by being measured directly. The parameters can (and should) be updated as the technology advances.

Elsewhere, it was concluded[1] that under certain conditions the voluntary visits to the robot evens out other facility use throughout day and night to a continuous-time stochastic process. This process was quantified in terms of a theoretical Probability Distribution (PD), which creates the opportunity to design the barn as a stochastic system. A closed queuing network model was developed for designing RMB[2,3]. The simulation model presented below, requires less simplifying assumptions than the network model, and improves communication between barn operators and designers. Simulation experiments allow equipment and layout to be evaluated jointly, and highlight potential design options before the barn is 'alive'; an initial design can be fine-tuned to produce a balanced system, a so-called 'optimal layout'. The simulation is intended for research as well as practical application.

2. The objective of this study

The objective of this study was to design an optimal RMB, customised for a given farmer or site. Optimal design balances adequate capacity against over-capacity. This can be achieved by developing a systematic design approach, integrating cows' behaviour, farm routines, feeding procedures, management practices, and scale-drawing. Using mathematical modelling, and computer simulation, enables a unique solution, specific to a given farm to be provided within a reasonable time.

3. Approaches for integrated design

The 'RMB system' has been defined as a '*discrete-event dynamic system*'([1]), affected by farm routines, feeding procedures, and management practices, that need to be taken into account when designing the layout of a barn. Theoretically, it is easy to design a barn which always has enough internal space - simply make it too big; but this is clearly a waste of money. Optimal design balances the cost of adequate capacity against the cost of over-capacity. Since an RMB is a discrete-event dynamic system, such a balance will vary over time, depending on equipment, farmer's preference (or personality), management attitude, etc.

The simplest type of design model is a *scale-drawing* of the building. However, a scale model is static; it cannot show how the various factors interact dynamically (Pidd[4]). Sometimes, *mathematical models* can solve a layout problem[3]. These apply techniques such as branch-and-bound, dynamic programming, queuing network, Markov chains or graph theory - a source of 'easy-to-formulate' but 'not-so-easy to solve' objective functions. While small (sometimes, artificial) problems of finding a 'perfect' layout or routine, can be solved by these techniques, large realistic problems often remain intractable. Simulation techniques offer a way of overcoming these disadvantages. *Computer simulation* does not require the same degree of simplification. The strength of simulation is its capability to deal with complex situations, which the mathematical approaches often fail to handle their complexity. Simulation is applied in many areas because of its flexibility, simplicity, and realism[5]. It allows quite realistic modelling of the barn, making use of animation, which provides a more natural approach for interfacing with farmer's expertise. And it allows all the factors that the farmer would like to integrate into his model to be introduced.

In this study we used Arena 3.1, which is a simulation programming language (SPL) with Visual Interactive Simulation (VIS); Object-orientated (O-O), including dynamic graphic display (DGD). These recent developments in simulation techniques have increased the modelling power, enhance their potential value in RMB design, enable complex barns to be mastered, and actually allows modelling of the RMB.

SPL facilitates the building of executable computer models for carrying out simulation experiments (Pidd[6]; Hlupic[7]; Van der Zee[8]). VIS and DGD illustrate the outputs of simulation models and alternative decision strategies. Bell[9], and Kirkpatrick and Bell[10] have reviewed VIS. O-O promises benefits such as one-to-one mapping of real-world objects; and improved program readability, maintainability and extensibility (Pidd[11]). For all these topics there is specialised literature, e.g., Law and McComas[12], and Kleijnen and van Groenendaal[13].

The solution for coupling the drawing of the barn with the simulation kernel was to load a DXF file containing the scale-drawing of the given barn into the simulation software. A DXF file can be created by most of CAD software (e.g., Cadkey[14]; Autocad[15]). The integration of mathematical model, scale-drawing and computer simulation provides the integrated design tool, required for this dynamic RMB system.

4. Simulation in designing barns

Simulation has become an important tool for designing factories, manufacturing systems, schools, supermarkets, banks, etc ([16-22]). As yet, however, these techniques have not been used to design complete dairy barns. Very few researchers dealing with barn planning have used simulation. Van Elderen[23] showed that simulation is a fruitful tool to investigate the influence of herd size, amount of milk per milking, cows' behaviour, selection units, etc., on the performance of the robot. Sonck[24] concluded that simulation is a powerful tool for labour planning. Others[25-33] have developed simulation models of milking parlours. Gonyou *et al.*[34] proposed the use of 'animats', computer simulated artificial animals, in designing pens for pigs. A general discussion of the use of 'animats' in social and spacing behaviour was presented by Stricklin *et al.*[35]. None of these authors, however, has developed a complete simulation methodology resulting in a practical tool to achieve an optimal design of the entire RMB as one balanced system.

5. Development of the model

5.1 Modelling approach, level of detail and 'process logic'

A modular approach is the basis of this simulation model. The system (barn) is broken down into five modules whose interactions produce the barn behaviour; they are the barn facilities (milking robot, CSF, forage lane, water troughs and cubicles). Additional components can be added to the model as needed, in order to reach a required degree of complexity. On the other hand, over-modelling (too much detail) increases the likelihood of errors and can lengthen the project duration, while not providing better quantitative results (Arena user's guide[36]; Law[37]). Different levels of detail were used in different sections of the model; namely only those details absolutely necessary to support the decisions to be made. A barn is modelled using a *process orientation*, i.e., study the flow of cows (entities) through the barn facilities, and graphically representing of the processes through which these entities pass, as they progress through the barn (system). Cows are the primary entities in the model, and each has four important attributes: a number, a picture, a most recent milking time, and a most recent concentrate consumption time (see *Fig.* 1). When needed, it is possible to add details such as a cow's individual milk yield, social priority (dominance in the herd), according to the decision to be made.

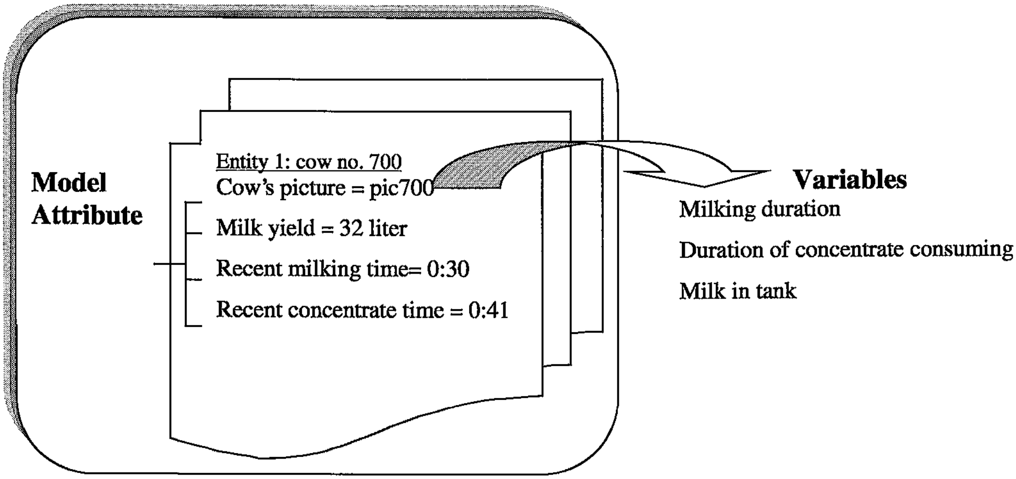

Figure 1. User-defined attributes and variables of an individual cow

The *process* denotes the sequence of operations or activities through which entities progress. For example, in the robot, a process may consist of entering the stall, followed by cluster attachment, milking, feeding, cluster detachment, and departure. In the CSF, a process may consist of entering, waiting for concentrate, eating, and departure.

Modules represent the barn's facilities, where the processes take place. Each module represents one facility. The cows (*entities*) pass repeatedly through the five facilities (*modules*). In a facility, there are parallel *resources*, which have the same service time, depending on the cow's attributes.

Cows first enter the barn in the *arrive module* and are immediately assigned individual attributes (*Fig.* 1). At the same time, each cow is sent to one of the facilities in the barn, according to the farmer's management practice. The farmer can choose where to locate the *source* of the cows; for instance, location of the source in front of the robot represents the grazing (cf. Sonck[38];). Locating the source in the forage lane represents a non-continuous feeding situation, i.e., all the cows see the distribution wagon and hurry to the forage at once. In any case, the influence of that initial condition vanishes after a few hours (see below). Then, the cows pass continuously through the modules. When a service (concentrate eating/ forage eating/ drinking/ laying/ milking) is completed, the cow proceeds via the *chance module* to anther facility, according to transition probabilities. If a *resource* is empty when a cow arrives, the cow stays there for '*service time*' minutes; otherwise, the cow is routed to a queue in front of the facility and her colour is changed to red. A cow in a 'working mode' is green, and a cow in 'transit mode' between facilities is blue.

Logic modules mimic instructions and logic control within the barn routine (e.g., 'six-hour concentrate time window', 'at least six-hour milking interval', 'one-way gate'), the rules which govern the behaviour of the barn. The rules were based on empirical data recorded by Halachmi *et al.*[1], and were refined in discussions with the team working on the project. An RMB contains sources of randomness. It is necessary to represent each source by a probability distribution (PD) rather than simply by its mean value (Law *et al.*[39]). Table 1 shows the PDs used. These PDs were fitted to data acquired by Halachmi *et al.*[1].

Table 1. Model's probability distribution of "service time"

Source of randomness	Distribution
Rewarded visit to the concentrate feeder	Normal(8.65, 3.43)
Unrewarded visit	Log-Normal(2.05, 1.75)
Milking visit to the robot	Normal(8.87 , 2.24)
Non-milking visit to the robot	Weibull (0.0727, 0.906)
Visit to the forage-lane	63*Beta(1.99, 5.37)
Visit to the water trough	Gamma(1.55 ,2.07)
Cubicles :	
including first 10min	10+529*Beta(0.911 , 4.08)
excluding first 10min	Weibull (17.5, 0.42)

Animation represents the system graphically (*Fig.* 3), and reports results as a set of *statistics*, such as equipment utilisation and the length of the queue of cows waiting to use the barn facilities. The *statistics* keep track of the state of the barn, and record changes that affect the barn components.

5.2 Model variables

The RMB simulation assesses performance in terms of equipment utilization and the number of cows in a queue, according to the following 10 measures. The first five are 'equipment-oriented' and the last five are 'cow-oriented':

1. *Concentrate feeder utilization,*
2. *Forage lane utilization,*

3. *Water trough utilization,*
4. *Cubicle utilization,*
5. *Robot utilization,*
6. *Queue length at the concentrate feeder,*
7. *Queue length in the forage lane,*
8. *Queue length at the water troughs*
9. *Queue length at the cubicle,* and
10. *Queue length at the milking robot.*

Factors can be changed between runs (e.g., herd-size, facility allocation) and between cows (e.g., milking duration, milk yield). During a run, the herd size is constant; neither entry nor exit from the barn by a cow is permitted.

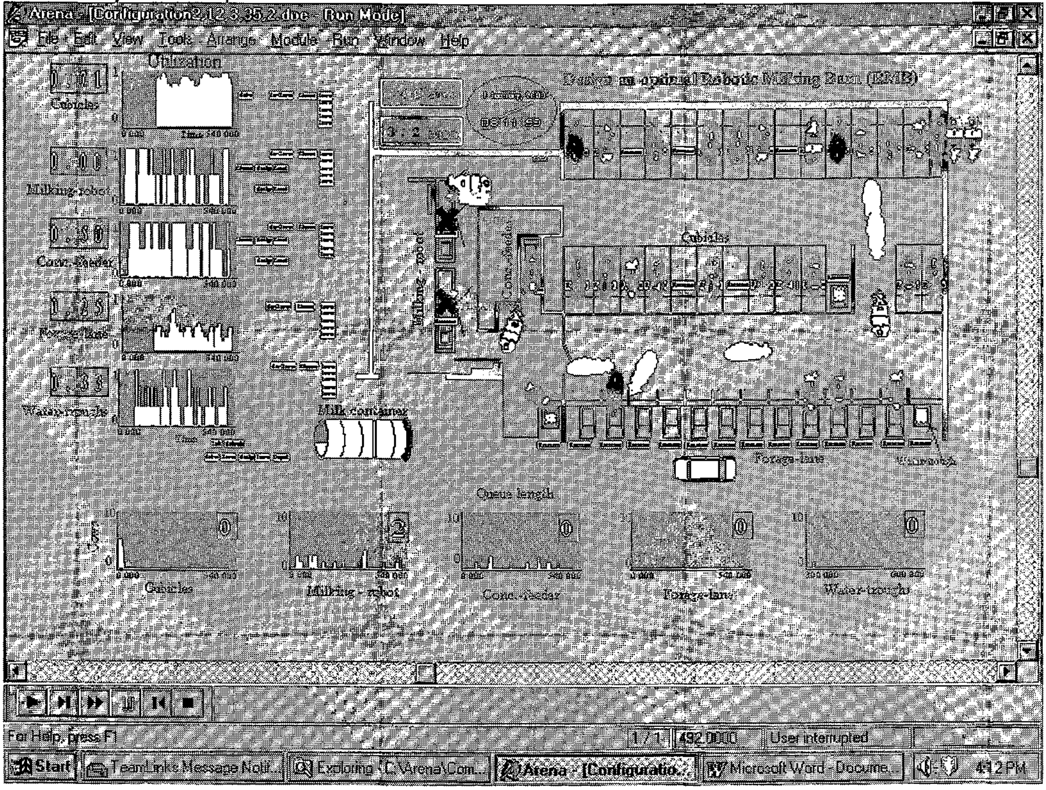

Figure 3. "RMB simulation" of configuration B

Two concentrate feeders, 12 forage-lane positions, three water troughs, 35 cubicles, 2 robot stalls, 40 cows at 8:12 am. The clock at the top of the picture shows the simulated time. Next to the left, number of cows in the barn, and the expected milkings per cow per day (MCD). On the left side of the screen is a utilisation graph for each facility. The graphs of the queue-length are located at the bottom. A digital number near a graph is the current value, while the graph keeps track of the historical values during the preceding 540 minutes. The scale-drawing is shown at the centre of the computer-screen. During the simulation run, all the cows and the milk-tanker are shown moving as in real life, only speeded up. Vivid colours indicate a cow's state: a green cow is in a "working mode", occupying a facility, eating, being milked, or resting; a blue cow is in a "walking state", walking between facilities or idle; a cow in a queue, waiting for an unavailable facility is red. Two red cows in front of the robot are waiting in a virtual queue. The robot is "on cleaning", not available (marked by "X"), from 08:00 to 08:30 daily. Every morning, around 8 o'clock, the milk-truck (the car icon) is driven slowly from the right side of the screen toward the milk tank, where it parks, empties the tank, and continues to a neighbouring farm.

6. Model verification and validation

The modeller's task is to produce a simplified yet valid abstraction of the barn of interest. The 'perfect model' would be the real system itself (by definition, any model is a simplification of reality[40]), in practice, however, the model should be 'good enough', in accordance with the goals of the model[41,42]. Full black-box validation[43] is impossible since the layout is still hypothetical, does not yet exist. Therefore, our working assumptions were:

- The main source of validation information is the farm records, the owner of the given barn, and operation of existing facilities.
- It may be possible to test parts of the model against parts of existing systems ('white-box validation'; see Pidd[43]).
- It is the modeller's responsibility to ensure that the statistical distributions employed are adequate for the intended barn.

A number of steps were taken to verify that the model was a reasonable representation of reality:

1. The RMB simulation repeatedly passed the 'face validity' test; several people familiar with the barn found the model's animated behaviour mimicked that of the real system.
2. The RMB simulation was compared with real barn measurements, using familiar validation techniques: the 'correlated inspection approach', 'residual errors examination', the 'repeatability test', 'problem of initial transient', and the 'time plot of important variables'.
3. Several consistency checks were performed, such as making incremental increases to herd size (number of cows) and seeing that they led to reasonable and steadily increasing values for the average waiting time required to enter the facility.
4. The RMB simulation was subjected to 'extreme condition' tests, such as setting the herd size to extremely high levels. Under such conditions, the RMB simulation still behaved reasonably.
5. The model was executed using ARENA standard edition, a well-known O-O language, which contains pre-programmed modules that should reduce the likelihood of programming error (Kelton *et al.*[44]).
6. The model's execution was checked interactively using ARENA's debugging capabilities, so as to examine the attributes of any entity and the value of any variable during a run.

6.1. The correlated inspection approach

The system and the model were compared by driving the model with historical system input data, rather than samples from probability distributions, and then comparing the model and the system outputs (*Fig.* 4). Thus, the system and the model experience exactly the same random variability of input, which should result in a statistically more valid comparison (Law and Kelton[45]: 'correlated inspection approach'; Kleijnen *et al*[46]: 'trace-driven simulation').

A simulation driven by random inputs (the 'PDs') will produce random outputs. Let X_i be the actual data (measured) for time i, and Y_i the forecasted data (generated by the model) for time i, then the residual errors (differences) are $D_i = X_i - Y_i$. The examination of the residual errors (or error of fit) is important for deciding on the appropriateness of a given model (Makridakis *et al.*[47]). If the errors are essentially random, then the model may be a good one. If the errors show any kind of pattern, then the model is not taking care of all the systematic information in the data set. In analysing errors we examined the following: 1) visual results, 2) mean of residual errors; and 3) standard deviation of residual errors.

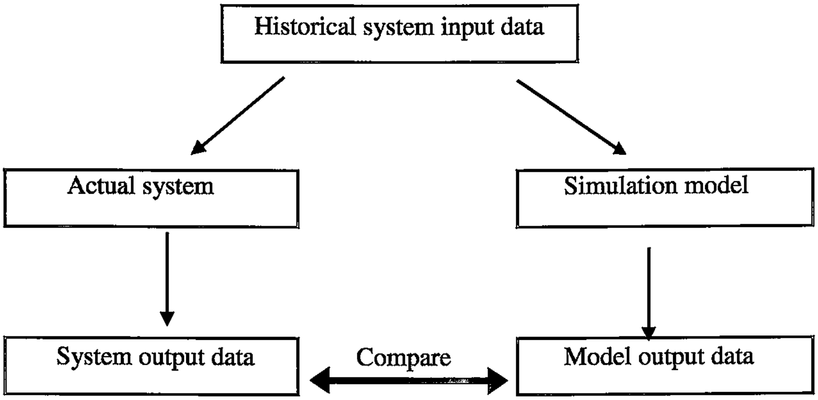

Figure 4. Model validation; the correlated inspection approach

Figure 5 plots the histogram of the residual errors (D_i) of the sub-models (barn facilities): forage lane (*Fig.*5a), water troughs (*Fig.*5b), cubicles (*Fig.*5c), CSF (*Fig.*5d), and milking robot (*Fig.*5e). It appears that the errors were often quite large, and they were essentially random. The 'quite large' is a result of a wide variability that is typical of animal behaviour data. The 'essentially random' means that the model is taking care of all the systematic information, which suggests that the model is valid.

In order to validate the milking frequency (average number of milkings per cow per day, so-called MCD), which is an output of the entire model (not a sub-model), we follow 'novel regression test'. The sums $Q_i = X_i + Y_i$, the regression D on Q is $E(D/Q=q)=\gamma_0 + \gamma_1 q$, and *F*-statistic were calculated. Common means of X and Y imply E(D)=0. If *F*-statistic is significantly low, we conclude that the simulation model meets stringent validation requirements. For theoretical consideration and equations in details refer to Kleijnen *et al*[46] (equations 1 to 6). Figure 5f suggests that the model is statistically valid (*F*-statistic<19.4).

6.2 The confidence interval approach

In order to determine whether the model is an accurate representation of the system, let Xi be a set of observations from the real system, and Yi be a set of data from the model. Since a model is only an approximation of reality, the null hypothesis $Ho: x_i = y_i$ will clearly be false in almost all cases. The confidence interval provides an indication of the magnitude by which x_i differs from y_i. We shall attempt to compare the model with the system by constructing a confidence interval $Z = \overline{X} - \overline{Y}$. Table 2 compares experiment (by Halachmi *et al.*[1]) and model output data from 10 days by using the paired-t approach, based on a fixed-sample-size procedure (Law and Kelton[45]). Since zero falls within the interval, we can claim with approximately 90% confidence that $\overline{Y}$ does not statistically differ from $\overline{X}$.

Note: since the samples had been taken from day 5 to day 14, well after the warming-up period, the influence of the initial condition had disappeared and the system can be considered as 'steady-state', so that each day can be treated as an independent replication.

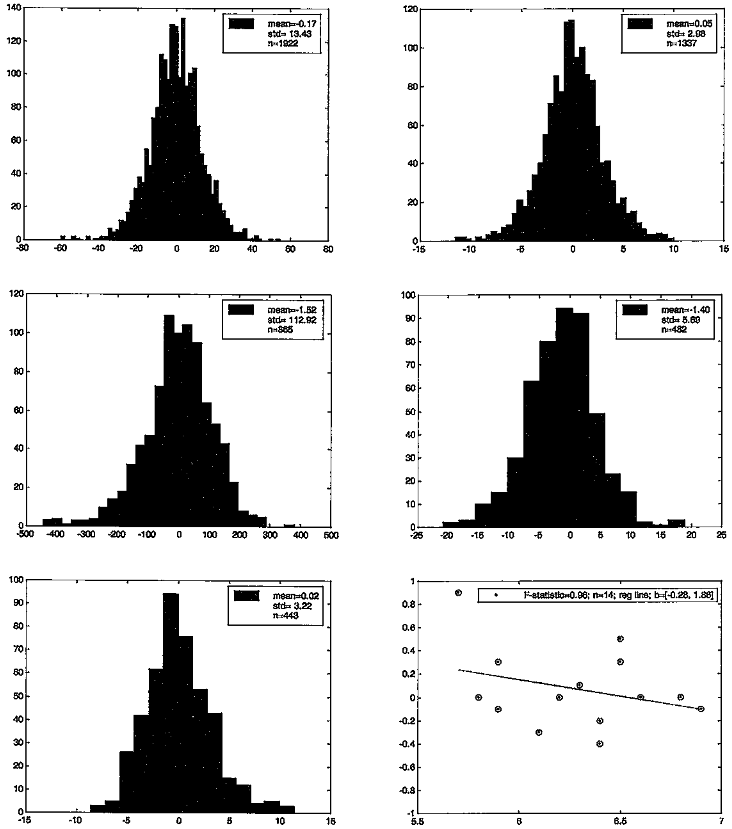

Figure 5. Model validation; residual analysis of the forage lane (a); the water troughs (b); the cubicles (c); the concentrate self-feeder (rewarded visits, d); the milking robot (rewarded visits, e), and novel regression test of milking frequency (f)

6.3 The problem of the initial transient

In the simulation literature, this problem is called the 'start-up problem' or 'initial-data deletion'. The idea is to disregard a certain number of observations from the beginning of a run. One simple and effective technique to determine the warm-up period is graphical analysis. In *Fig.* 6 we plot the time variation of the average queue at the milking robot. In this case, two robot stalls were simulated for 40 cows; this ratio should normally result in no queue in front of the robot. But the initial condition was that all the cows were 'pushed' into the cubicle area. This mimics all the cows arriving from grazing at once, and moving into the waiting area in front of the robot, being milked, and being allowed to get concentrate. Obviously such a situation, in which all the cows hurry to the robot, causes pressure on the robot. The simulation model mimics that extreme circumstance quite well. Furthermore, it shows that the overcrowding will vanish within about two hours (also the warm-up period), which is an important piece of information in itself, also in agreement with the observation by Uetake *et al.*[48]. In the light of the inherent variability of cows' behaviour, it was found (Fig 6) that the model had to run for a simulated time of at least 4 h to achieve meaningful results; it takes about 2.5 min of real time.

Table 2. Cow throughput: results of 10 replicated days, model and experiment

	Concentrate		Forage		Water		Cubicles		Robot	
Day	Model	Exp	Model	Exp	Model	Exp	Model	Exp	Model	Exp
1	87	91	148	135	105	95	187	137	93	91
2	115	89	168	119	133	81	199	128	118	94
3	89	99	127	136	93	112	161	163	98	101
4	75	69	123	130	100	98	137	137	73	68
5	87	96	132	136	98	104	151	138	93	91
6	102	105	143	141	108	88	177	149	110	108
7	80	106	135	153	102	88	155	149	87	108
8	83	117	144	144	108	86	163	153	89	125
9	85	95	140	163	96	87	167	250	93	102
10	63	78	95	115	63	95	116	135	67	86
Mean	86.6	94.5	135.5	137.2	100.6	93.4	161.3	153.9	92.1	97.4
Confidence Interval (95%)	[-1.7	17.5]	[-10.4	13.8]	[-20.7	6.3]	[-31.3	16.5]	[-4.4	15.0]

Exp, experiment with real (non-simulated barn)

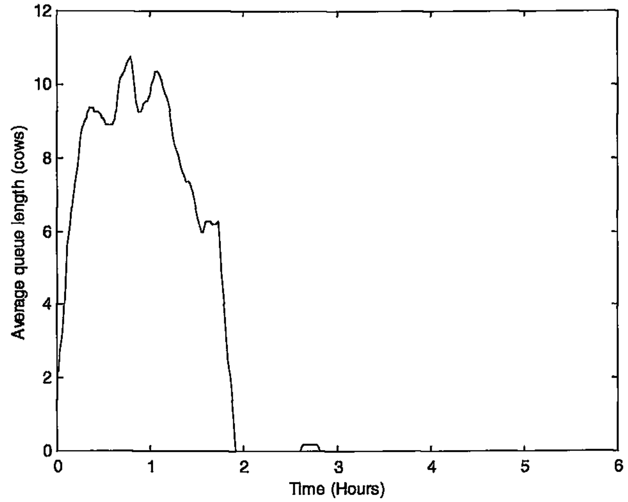

Figure 6. The problem of initial transient; queue length at the milking robot

6.3 Time plots of important variables

Since a cow's behaviour varies with time, we need an indication of how system performance changes dynamically over time. Animation provides insight into short-term dynamic behaviour, but it does not give an easily interpreted record of system performance over the entire length of the simulation. A time plot can bridge the gap; for example, a plot of queue size against time (*Fig.* 7) provides information through the day on which a 'robot facility' has sufficient milking capacity, and also on the floor space or capacity for the queue required at 'busy time'. It can be seen that the robot has an activity peak, every day at the beginning of the second time-window (06:00-12:00). This can be explained by the farm routines and the cows' behaviour during this time: 1) the robot is 'being cleaned', inaccessible for about half an hour, 2) most of the cows awake from the night with full udders, and are allowed and eager to eat concentrate (the concentrate time-window also opens at 06:00), and 3) around 08:00, the farmer distributes the forage, which encourages the cows' activity. So, 'time plots' provide an easy means to understand of the long-term dynamic behaviour of the system.

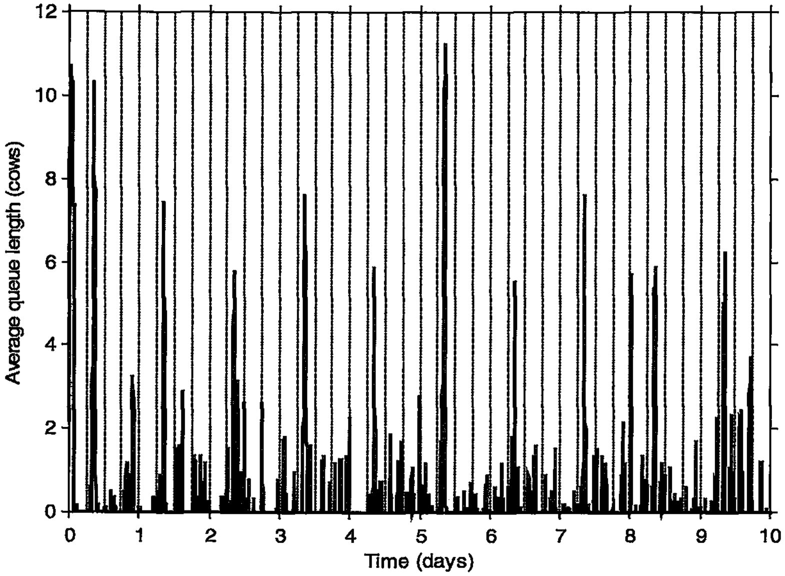

Figure 7. Time plot of important variable, queue length at the milking robot

7. Results of simulation experiments

The result of the study is the methodology itself, that is the method, the algorithm, or the 'technique' that has been developed and implemented into a software application. The possibilities of interactive creative design are numerous, even for a single farm. Therefore, in order to explain the proposed methodology, its capability and its scope within a given practical situation, only a few simple possibilities were selected.

A crucial application of the RMB simulation lies in comparing design alternatives before implementation. In this section we compare the outputs from several different simulation runs that might represent competing barn designs.

7.1 Aspiration level ('design specifications')

The following specifications were imposed:

(1) a typical Dutch dairy barn; (2) two-rows cubicle housing; (3) one forage lane; (4) CSF stand-alone, in addition to that of the robot; (5) at least one water trough in each barn section; (6) Feeding strategy: a) forage available throughout the day, b) four concentrate time windows per day; (7) maximal average waiting-time, a cow waits for a facility: a) robot 9 min., b) CSF 2 min., c) all other facilities 0.05 min (3 sec.); (8) minimal facility utilisation (busy time): a) robot 60%, b) CSF 40 %, c) Cubicles 75 %, d) Forage lane 25 %, e) Water troughs 10 %

These requirements were defined according to common practice in state-of-the-art dairy farms[49].

7.2 Determining the design starting point

To determine the mathematical optimal starting point (i.e., to determine system design A); let us do a simple queuing-type analysis of the given barn. Arrival rate (λ_i) and service rate (μ_i) at facility i (CSF, forage lane water troughs, cubicles, milking robot), were measured by Halachmi *et al.*,[1]. In order to have sufficient capacity, the utilisation $\rho_i = \frac{\lambda_i}{c_i \mu_i}$ must be less than 1, therefore, if we solve the equation for $\rho=1$, we obtain the required number of servers (c_i) for facility i, which we round up. Using the conditional probability (Ross[50]), the mean service times at CSF and milking robot are: $S_{concentrate} = P_{eaters}*S_{eaters}+P_{non\text{-}eaters}*S_{non\text{-}eaters}$; $S_{robot} = P_{milked}*S_{milked}+P_{non\text{-}milked}*S_{non\text{-}milked}$, where 'P' denotes the population proportion, and S the 'service time'. For example, P_{eaters} means the proportion of rewarded visits, which takes (on average) S_{eaters} minutes. $P_{non\text{-}eaters}$ is the proportion of non-rewarded visits, which take $S_{non\text{-}eaters}$ minutes. The same holds for the milking robot, and the values of P and S described by Halachmi *et al.*[1]. According to the experiment conditions[1], it was assumed that the service time would satisfy the animal welfare needs, independently of the number of cows in the barn. The arrival rates certainly depend on the number of cows circulating in the barn. In that experiment 10 cows were monitored, but the arrival rate would have to be adjusted to predict the effect of, say 100 cows. An estimate is that the arrival rate rises linearly with the number of cows in the herd (H); $\lambda_i = \frac{\lambda_{i10} H}{10}$, where $\lambda_{i\,10}$ is the arrival rate of 10 cows, as found empirically by Halachmi *et al.*,[1]. A summary of the calculation of all the five facilities, for 40 cows, is given in Table 3. We see that two, seven, one, 30, and two positions are supposedly required for facilities i=1,2,...,5, respectively, defined as 'system design A'. System design A is the mathematically optimal solution used as a basis for further simulations.

Table 3: Queuing analysis; required capacity for 40 cows

Facility	arrival rate (cows/hour)	service rate (cows/hour)	Required number of positions	
Concentrate feeder	17.44	9.74	1.79	→ 2 feeders
Forage lane	26.17	3.99	6.55	→ 7 lane positions
Water troughs	18.03	18.87	0.96	→ 1 water troughs
Cubicles	29.70	1.01	29.42	→ 30 cubicles
Robot	17.88	12.01	1.49	→ 2 milking stalls

Results from simulated system, design A

A summary of system design A is given in Table 4. The water trough waiting time is 2.4 min, which exceeds the specifications (marked by bold letters). Furthermore, a specification was one trough per section, which mean at-least three troughs in the barn. The waiting times in the forage lane, and cubicles also exceed the specifications. The robot utilisation level is below the specification. Therefore the next simulation run, 'simulated system, design B' included the following *ad-hoc* additions: two water troughs, five forage positions, and five cubicles.

Table 4. Simulation results for facility configuration A, starting design

Facility	Waiting time		Utilisation		Observations
	Average (min)	Half-width* (95%)	Average	Half-width (95%)	
Concentrate feeder (2)	1.12	.218	.422	.014	2892
Forage lane (7)	.304	.119	.547	.017	4461
Water troughs (1)	2.44	.349	.526	.023	3296
Cubicles (30)	2.42	.384	.937	.007	5186
Milking robot (2)	.953	.222	.325	.015	3038
Total time	7.23				

Results from simulated system, design B

As Table 5 and *Fig.* 3 (the animation) show, the total waiting time has dropped from 7.23 to 2.23 min. All the aspiration levels have been fulfilled, excluding the robot utilisation. Obviously two robot stalls are too many, therefore, we removed one robot stall, and repeated the run (table 6).

Table 5. Configuration B; add five forage positions, two water troughs, and five cubicles

Facility	Waiting time		Utilisation		Observations
	Average (min)	Half-width (95%)	Average	Half-width (95%)	
Concentrate feeder (2)	1.26	.292	.440	.014	3066
Forage lane (12)	<.00	<.00	.325	.009	4550
Water troughs (3)	.026	.014	.174	.007	3276
Cubicles (35)	.060	.037	.826	.006	5380
Milking robot (2)	.888	-----	.341	.021	3212
Total time	2.23				

Results from simulated system, design C

Table 6 shows that the average waiting time for milking has increased to 8.2 min, which is still within the aspiration level. Thus system design C seems to be appropriate.

Table 6. Configuration C; remove one robot stall

Facility	Waiting time		Utilization		Observations
	Average (min)	Half-width (95%)	Average	Half-width (95%)	
Concentrate feeder (2)	1.45	.255	.434	.013	2922
Forage lane (12)	<.00	<.00	.305	(Corr)	4323
Water troughs (3)	.017	.008	.167	(Corr)	3125
Cubicles (35)	.038	-----	.807	.009	5141
Milking robot (1)	**8.18**	1.63	.637	.021	3086
Total time	**9.69**				

8. Discussion

8.1 Simulation results

In practice, however, there are different farms, moreover, farmers may assume different scenarios, and may select different design specifications, based on different associated costs. So our major contribution is the methodology we derived in this paper.

From an economic point of view, the simulation shows a reduction of about 70% in the forage-lane positions (usually the ratio is 1:1 positions to cows) and of about 10% in the number of cubicles, without violating the aspiration level. From the cow's point of view there is little waiting time, and important resources are available reasonably often.

Water troughs are relatively cheap facilities, their function for high-yielding cows is physiologically important, and it is recommended by all standards to have troughs in each barn section. The function of the cubicles is also important for resting, ruminating, and to avoid confrontation. A robot is relatively expensive therefore, its utilization should be relatively high. Accordingly, the mentioned above specifications were defined.

Robot companies update the robot software regularly, which results in better teat attachment, which improves the robot capacity. The data used in the present paper were acquired at the beginning of 1997. The RMB simulation parameters will have to be updated if robot software is updated. It can be assumed that the use of updated parameters will improve robot availability.

An example for 'interaction between facilities' is the reduction in cubicle queuing time when the number of milking stalls was reduced from two to one (Table 6). Not surprisingly, the 'queue' shifted to the robot.

8.2 User-friendly interface

The 'user-friendly interface' (the computer screen), is designed to be easily understood by the ultimate users of the model. The same screen combines direct observation into the animated barn, and simultaneous examination of the statistics. In this way, it transforms the mathematical model into a communicative form for non-experts. For instance, the proposed layout configuration B is animated: see *Fig.* 3. By simply looking at these animated cows 'circulating' among animated facilities, we can see whether there is enough capacity, and enough floor space in that particular barn.

The simulation speed can be changed from very slow, to examine in detail the execution of control rules, to very fast, to examine the development of bottlenecks. At maximum speed, with live animation, this model can simulate 8 h of activity in approximately 5 min; without live animation, 14 days can be simulated in less than 15 sec.

The mathematical model would lack the ability to incorporate all specific demands, such as a water trough in each section (Table 3), and the easily-understood communicative phase with the user.

This user-friendly interface solves these problems as well as making the mathematical model (integrating cow behaviour, farm routines, feeding procedures, management practices, scale-drawing, etc.) into a practical tool for designing RMBs. Congestion during a particular time of the day might be caused by management practices (e.g. grouping the cows for forage feeding or grazing). This congestion influences the area design of each section in the barn, and may suggest a different management practice. Such congestion is not readily identifiable from the reports, but is very apparent from the visual output of the model.

8.3 Advantages and disadvantages

Using the new methodology and rigid specifications for 40 cows in a specific farm, the simulation suggests the following:

1. The farmer will build 12 forage lane positions rather than 40, and 35 cubicles rather than 40.
2. The robot's waiting area (i.e. floor space for queuing) should have a capacity of eight cows during its peak time.
3. To match its peak time, the CSF's waiting area, should have a capacity of 6 cows.
4. The proposed design can achieve the desired standard or demands (in waiting time, milking frequency, etc).
5. The animation allows a range of personnel unfamiliar with milking-robots to appreciate, how the new RMB would operate.

Although the model's analytical benefits are considerable, one other important benefit is that the farmer gains the assurance before building that the proposed design will actually meet his specified requirements.

Further advantages of the RMB simulation:

1. Animal welfare: simulation allows experiment without doing any harm to animals or to facilities. For example, one objective of a simulation study may be to estimate the effects of extreme conditions, i.e. simulated Limousin bulls cause little damage when they run out of food or space in a virtual barn ...
2. Lower costs: although simulation may require skilled manpower, physical construction and refitting of different layouts are usually more expensive.
3. Less time is needed to carry out an experiment, because it is often possible to simulate weeks, months or even year in just a few seconds of computer time. Consequently, a long-range programme (policy) may be tested in a relatively short time.
4. Ease of replication: whereas real barn rarely allows exact replication of experiments, simulation does.
5. Simulation experiments allow factors that are uncontrollable in reality to be controlled. This helps to focus our conclusions more sharply.

6. Simulation yields a system-wide view of the effects of local changes. The impact of a change at a particular facility, on this facility may be predictable. On the other hand, it might be impossible to predict the impact of this change on the performance of the overall system.

Discrete event simulation has some drawbacks for barn modelling, implying the following needs:

1. A new type of data collection, to deal with cows' behaviour and facility usage; it should not depend on any specific layout (Halachmi *et al.*[1]). And, sophisticated statistical tools are needed to study the stochastic nature of facility usage, (e.g. Arsham[51]).
2. Heavy computations, to obtain data analysis and visual simulation of many cows.
3. Close collaboration between dairy researchers and computer scientists, who are usually not located in the same laboratory or barn. This is necessary for both model design and validation. Complex programming problems need to be solved.

The main limitation of simulation lies in its *ad-hoc* character: we observe the simulation responses only for the selected input combinations, i.e., there is no proof of the optimality of a solution. This is why our methodology starts with analytical/mathematical optimisation.

9. Conclusions

The proposed design methodology combined simulation and heuristic optimization overcomes the difficulties characterising the RMB system. Simulation experiments allow equipment and layouts to be evaluated jointly, and an initial design can be fine-tuned to produce a balanced system, a so-called 'optimal layout', within reasonable time, specific for a given farm. By executing the suggested methodology, step by step, we designed an optimal RMB, meeting both economic (in terms of facility utilization) and animal welfare needs. If a simulation study had not been performed and if a bottleneck had been discovered after installation, the cost of retrofitting extra capacity could have been significant.

10. Further developments

Additional data acquisition from different farms, robot companies, CSFs, cow breeds, etc.,) would make the model more reliable. The model is a 'discrete-event' as well as 'continuous process' simulation. e.g., a cow leaving a facility (an event that takes place at distinct point in time); and milk flowing through the pipes during a milking (continuous processes). 'Obviously, the programming of combined continuous/ discrete-event is a challenge' (Kleijnen and Groenendaal[13]). It was programmed in order to illustrate the capability to deal with both, in parallel. In the future, as needed, ammonia emission, manure storage and other continuous processes can be modelled in the same way.

It would seem to develop advisable commercial software, to enable persons with no simulation/programming expertise to conduct simulation experiments.

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Chapter 5

Validation of the model

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Abstract

Because milking robots are a recent technological development, there are few precedents and little experience to draw upon when designing robotic milking barns. There is wide diversity among farms, so the optimal layout of the robotic milking barn (RMB) varies accordingly. Using a behaviour-based simulation model, the design focused on optimal facility allocation and its relation with feeding routine, herd size, management practices, etc. This paper applies validation research, compares data on real and simulated RMBs. Measurements from a real robotic farm with 10, 20, and 30 cows are compared with simulation data. The simulation model appears to be a valid, accurate representation of the real system, under commercially feasible conditions. This hypothesis is tested statistically and is not rejected at α=2.5%. So the conclusion is that the model is a practical design tool, enabling the designer to optimise facility allocation and barn layout.

Keywords: Validation, Simulation, Milking robot, Cow, Agricultural systems

1. Introduction

At the beginning of the 20th century, innovations such as tractors, milking machines, and fertilisers revolutionised farm productivity. Unfortunately, the workload of a dairy farmer is still considerable. Robotic milking, which dispenses with the need for human involvement in the milking process, is the most recent innovation to offer major improvements to dairy farmers' working routine and quality of life.

Robotic milking saves labour; it affects cow behaviour, farm routine, feeding procedures, and management practices. All these aspects need to be taken into account when designing a robotic barn. In the Netherlands, more than 200 robots had been installed by the end of 1998 and, according to Ipema[1], between 5% and 20% of Dutch dairy farms will be equipped with a milking robot by the year 2005. Milking robots have been reviewed elsewhere[2-6].

Whereas the design of a conventional dairy barn is based on decades of experience, there is very little such experience with the robotic milking barn (RMB). Furthermore, there is wide diversity among farms; each farm has its individual characteristics such as building structure, ventilation, existing facilities; each farmer has his own feeding routine, management practice, preferred cow routine in the barn, etc. The optimal RMB layout, therefore, differs among farms. There is clearly a need for a methodology for RMB design that is universally applicable but also adjustable to every farmer or site.

Simulation allows realistic modelling of the barn; its use of animation provides a more natural approach to interfacing with the farmer's expertise. As yet, however, only few dairy researchers involved in barn layout planning have used simulation[7]. Another paper[7] describes the development of a behaviour-based simulation model that enables the designer to optimise facility allocation and barn layout. The present paper describes a study to determine whether this simulation model is 'valid', i.e. indeed is it an accurate representation of the real system?.

2. The validation concept

In general, the modeller's task is to produce a simplified yet valid abstraction of the real system of interest[8]. The 'perfect simulation model' would be the real system itself; by definition, any model is a simplification of reality[9]. In practice, however, the model should be 'satisficing', in accordance with the goals of the model[10]. Law and Kelton[11] note that one way of validation is to compare data from real and simulated systems. Comparing output data from real and simulated systems makes more sense if both systems are observed under similar scenarios. For example, the behaviour of a grazing herd should not be compared with a simulated indoor herd, neither should barn activities subjected to a TMR (total mixed ratio) feeding routine be compared with simulated activities under a CSF (concentrate self-feeder) routine.

Under continuous robotic milking, the milking process is spread over the entire day and night. So around the clock, each cow arrives voluntarily, depending on its internal biological timing, and is milked individually. We quantified the stochastic nature of robotic milking frequency and other facilities usage (FU) in an RMB under conditions of maximum availability of facilities and independent of the barn layout[12]. This made it possible to allocate facilities optimally, based on known FU requirements. The FU had been measured under these conditions, in a loose housing system with 26 cubicles per 10 cows, 40% more forage positions than cows, and 2 robot stalls[12]. Floor space was 19.3 m^2 per cow, and the feeding routine was continuous supply (refilling every 30 minutes, 24 hours a day). These conditions may be said to represent a 'cow's paradise', only attainable under laboratory conditions. Data obtained from a 'laboratory experiment'[12] was entered into the model. Having found out that the farmer's usual feeding routine was twice a day, at 8 AM and 6 PM, we programmed this data, as well as the varying number of cows in the herd. After running the simulation program, we compared the time series of simulation output with a real barn, in a new experiment described below.

If FU by dairy cows is a continuous-time stochastic process, then queuing theory could be useful to model the RMB. The situation is then described as 'cows forming queues in front of service facilities', and the language of queuing theory can be used for modelling[12-14]. Unfortunately, 'discrete-event' management practices (such as silage feeding twice daily) interrupt the continuous-time stochastic process. Simulation overcomes this disadvantage. The strength of simulation is its capability to deal with complex situations, which the analytical approaches often fail to handle.

Behaviour-based simulation is a new integrated design tool for RMB, developed by Halachmi[7]. He investigated the model's validity by *correlated inspection*, *confidence intervals*, *initial transient*, *time plot of important variables*, and *sensitivity-analysis* approaches as recommended[11]. However, he used the same real-barn observations for both building the simulation model and validating it. Biological science requires that the results be repeatable in different experiments, with different barns and cows, i.e., under different farming conditions. In the study described below we investigated whether the simulation model[7] is valid under conditions differing from those under which the model was developed.

3. Real and simulated systems

We conducted two types of experiments: observation of cow behaviour in a real (non-simulated) barn and in a computer simulation. These two data sets were compared visually and statistically. In both, we varied an interesting parameter, namely the number of cows in the herd, and investigated its influence on the model's performance. Our measures of performance are the various utilisation percentages of different facilities.

3.1 Real system

In Dutch commercial farms with robotic milking the cows are usually given forage food twice a day: in the morning, fresh silage is distributed by tractor, and in the evening the remaining food is pushed closer to the cows. There are significantly fewer forage lane positions than cows (in our case: 12 feeding positions for 30 cows). One CSF is shared by up to 30 cows. The amount of floor space allotted to each cow is approximately 6-7m^2 (in our barn: 6.6 m^2). The number of cubicles is almost equal to the number of cows.

The real barn we used in our study had the following characteristics: Groups of ten, twenty, and thirty cows were kept in a loose housing system with cubicles, originally designed for thirty cows. Each situation was recorded during 21 days for each group, between March and May 1998, in a farm called 'De Vijf Roeden', located in Duiven, the Netherlands. During the third experiment, one cow died, which reduced the size of the third group to 29 cows.

The barn contained a two-stall Prolion milking robot combined with internal concentrate feeders (one milking box was closed), a forage lane with 12 troughs, one concentrate self-feeder, 30 cubicles and two water troughs that could easily be approached by cows from all sections of the barn; see *Fig. 1.* All the facilities were visible from anywhere in the barn. A one-way gate between the concentrate self-feeder and the forage food area forced cows to reach the concentrate feeder via the robot. The cows (Holstein-Friesian and Friesian Holland races) were accustomed to the facilities and the routine; they were two or more months into lactation.

In this herd, the average body weight was 650 kg for adults and 550 kg for first lactation. The average milk yield per cow was 35 kg per day, and contained 4.28% fat and 3.3% protein. The cows were selected for their good cluster attachment in robotic milking.

The cows were offered a mixed roughage ration containing 50% grass silage (175 g of CP/kg; 0.20MJ of NE$_L$), 50% maize silage (67 g of CP/kg; 0.22 MJ of NE$_L$), and 1.5 kg/cow of concentrate (220 g of CP/kg; 0.25 MJ of NE$_L$) for ad-libitum intake at the forage lane. Every morning, around

8:00 a.m., a commercial weighing mixer wagon (Lachish Ltd, Israel) was tractor-driven along the forage lane to fill the troughs with fresh silage. Around 6:00 p.m., forage was pushed manually toward the cows. The cows received 8 kg of concentrates per day in the CSF and one kg per milking in the milking robot. The feeding time-window of the concentrate feeder began every six hours, at 6:00 a.m., 12:00 p.m., 6:00 p.m., and 12:00 a.m. If a cow entered the CSF more than once within a six-hour period after the predefined fixed amount of concentrate had been dispensed, it was not offered any concentrate. Any left-over concentrate was added to the concentrate available for the next period. The robot was maintained and cleaned daily between 7:30 a.m. and 8:15 a.m. and between 10:00 p.m. and 10:45 p.m. Milking frequency was limited to four times per day, with more than 6 hours between consecutive milkings. If a cow entered the milking robot more than once within a 6-hour period, it was not milked, no concentrate was offered and it was obliged to leave the robot.

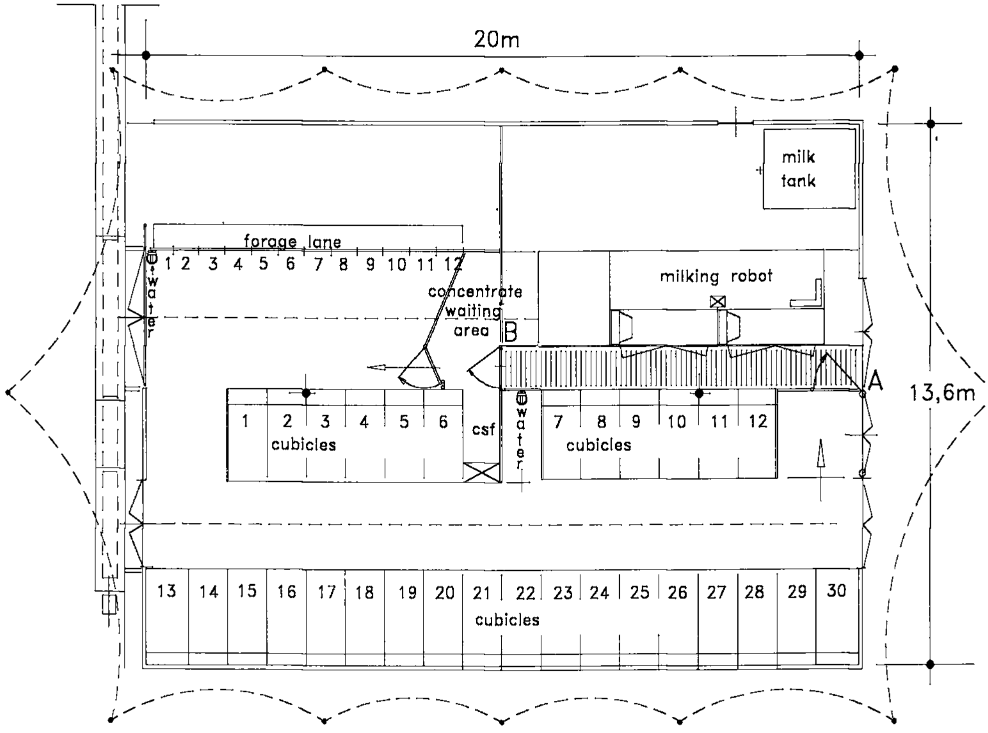

Figure 1. Layout of the real barn: one concentrate self-feeder (CSF), 12 forage-lane positions, 2 water troughs, 30 cubicles, 2 robot stalls

Every morning, a tractor filled the troughs. The cows saw the tractor and hurried forward to get fresh forage. They overcrowded the forage lane, all the lane positions were occupied and many cows waited nearby for an available feeding position. At the same time (around 8:00 a.m.) the milking robot was in cleaning mode. Disinfecting material was circulated in the robot's milk pipes, and the robot was out of operation for about 45 minutes. Also, the cows could not go through the robot on their way to the CSF, so each day includes terminating and start-up phases.

Information on all physical activities (feeding, drinking, milking, staying in the cubicles) was recorded automatically, either by sensors, by three video cameras during 24 hours a day or by electronic identification. Data on a cow's arrivals and departures from the barn facility were obtained by collecting the time of operation of each facility's clock or the video camera. A computer program written in Matlab[20] was used to sort and analyse the raw data. The measurements and the experiment are described in detail by Dzidic[15].

3.2 Simulation model

The simulation output was the average facility utilisation per hour over 30 days of activities for each herd size (10, 20, and 29 cows). In this simulation experiment, the usual feeding routine (twice a day, at 8 a.m. and 6 p.m.) was programmed in, plus the barn layout (*Fig.1*), and the varying number of cows in the herd. The simulation model is based on empirical data[12], and has been described in detail elsewhere[7]. The main principles are summarised below. A new version of the robot software was released at the beginning of 1998, so the robot's 'service time' parameter was updated to *Normal(8.3,2.76)*, instead of *Normal(8.87,2.24)*. All other parameters remained the same as described by Halachmi[7].

A modular approach formed the basis of this simulation model. The system (barn) was broken down into five modules, whose interactions produce the barn behaviour. These modules are the barn facilities: the milking robot, the CSF, the forage lane, the water troughs, and the cubicles. In a facility (*module)*, there are parallel *resources*, which have service times dependent on the cow's individual attributes.

A barn was modelled using *process orientation*, where a *process* denotes the sequence of operations or activities through which the cow progresses. For example, in the robot, a process may consist of a cow's entering the stall, followed by feeding, cluster attachment, milking, cluster detachment, and departure. In the CSF, a process may consist of a cow's entering, waiting for concentrate, eating, and departure.

If a *resource* is empty when a cow arrives, the cow stays there for '*service time*' minutes; otherwise, the cow is routed to a queue in front of the facility. In the animation the cow's colour is changed to red, a cow in 'working mode' is green, and a cow in 'transit mode' between facilities is blue.

In this study we used Arena 3.1[16], which is a simulation programming language with Visual Interactive Simulation (VIS); Object-orientation (O-O), including dynamic graphic display (DGD). A view of the system is presented graphically, showing the animated barn and a set of *statistics* such as equipment utilisation and length of the queue of cows waiting to use barn facilities. VIS and

DGD illustrate the outputs of simulation models and alternative decision strategies. O-O promises one-to-one mapping of real-world objects, and improved program readability, maintainability, and extensibility. There is specialised literature on all these topics, e.g., Law and McComas[17]. The solution for coupling the drawing of the barn with the simulation kernel was to load a DXF file containing the scale-drawing of the given barn into the simulation software; a DXF file can be created by most CAD software (e.g., Cadkey[18]; Autocad[19]). The *statistics* keep track of the state of the barn, and record changes that affect the barn components. Then these statistics were automatically transferred to Matlab[20] for further analysis. The integration of the mathematical model, scale-drawing, and computer simulation should provide the design tool required for a dynamic RMB. These recent developments in simulation techniques have increased modelling power, enhanced their potential value in RMB design, and enabled complex barns to be mastered.

4. Statistical validation

A simulation driven by random inputs will produce random outputs. If statistical testing is performed, then the correct statistics should be used. The visual analysis, traditional regression analysis, and Kleijnen's test[21] are described below.

4.1 Visual analysis

By visual analysis we mean 'eyeballing' the time series of the real and simulated systems to decide whether the simulation adequately reflects the real barn[22]. Since each day is a replication, i.e. we have multiple time series. The visual analysis was done using a *box plot*[23], in which the output of the real system was displayed as a box with lines at the lower quartile, median, and upper quartile values. The 'whiskers' are the lines extending from each end of the box to show the extent of the rest of the data (maximum and minimum values). On the boxes, the averages of the real and the simulated systems were drawn. For an example, see *Fig. 2* left column.

4.2 Traditional regression analysis

Let X_i and Y_i denote the real and simulated outputs respectively in observation i. In *traditional regression analysis* the ideal simulation model would mean $X_i=Y_i, \ \forall \ i$. This equality implies a perfect fit ($\rho_{xy}=1$). Thus, the regression line $Y=\beta_0 + \beta_1 X$ should have (H_0:) $\beta_0=0$ *and* $\beta_1=1$, i.e., a unit slope (45°) line through the origin (zero intercept). For more details and the associated *F-test* we refer to Kleijnen and van Groenendaal[22], p 209-210. The above criteria (perfect fit) are too stringent; they "too often reject valid simulation models"[21], the real and simulated systems should have the same mean, the same variance, and positively correlated responses.

4.3 Kleijnen's test

Kleijnen et al.[21] proposes an alternative test: Calculate the sum $Q_i=X_i+Y_i$, the differences $D_i=X_i-Y_i$, and the regression $E(D|Q=q)=\gamma_0 + \gamma_1 q$. Obviously, common means of X and Y imply E(D)=0; it can be proven that common variances imply zero correlation between D and Q;

together this gives (H_0:) $\gamma_0=0$ *and* $\gamma_1=0$. If the appropriate *F*-statistic is significantly high, we reject the hypothesis H_0 and conclude that the model is not valid.

The assumption of this test is that outputs of the real and simulated systems are identically and independently normally distributed. Since the output was an average, normality can be explained by the central limit theorem. A terminating simulation explains identically and independently among days, but not among hours. Therefore we did an additional *F* test (so-called F^{day}), where the measure was the 75% percentile per day (not per hour). We took the 75% percentile (defined by[23]) because (1) it is more scientific challenge than average; (2) we intend fitting also extreme utilasations that might accrued during feeding times. In our case, $F^{hour}_{22,2;0.975} \approx F^{day}_{19,2;0.975} \approx 39$ (2.5% significant level, 24 hours per day or 21 days of experiment per each group, the parameters D and Q applies two degrees of freedom).

5 Result of the validation experiments

5.1 Visual analysis

The average utilisation of the forage lane facility in the real and the simulated systems is illustrated in *Fig. 2*. The left column shows that, not surprisingly, utilisation increases with group size. Two peaks during forage feeding time (around 8:00 a.m. and 6:00 p.m.) dominated the time pattern of the cows' feeding behaviour. At these times the forage lane utilisation of the group of 29 cows reached 90%; this mean that it would be inadvisable to reduce the number of feeding positions. For the groups of 20 and 29 cows, the simulation followed the observations quite well, including the peaks during forage feeding time.

Observed cubicle utilisation never exceeded 0.75 (*Fig. 3* left), which suggests that it would be feasible to have fewer cubicles than cows without adversely affecting cow behaviour. During the night more cows were in the cubicles, and during the day more cows were in the forage lane (*Fig. 2* left). For the groups of 29 and 20 cows, the simulation follows the real observations quite well (*Fig. 3*). However for the group of 10 cows (upper row), the drop in cubicle utilisation during forage feeding time was not adequately followed by the simulation model.

Figure 4 (left) shows that observed robot utilisation was characterised by drastic fluctuations. For the groups of 20 and 29 cows, it can be seen that the simulation followed the average utilisation of the real system, including the peaks during forage feeding time. The 10 cows scenario is less adequately modelled.

Figure 5 shows large variety in observed CSF utilisation, which is typical of cow behavioural observations[24]. Nevertheless; the simulation mimicked the average observation quite well, except around 3:00 p.m.

5.2 Traditional regression analysis

In Table 1, the *traditional regression analysis* rejected two sub-models (F-statistic is significantly high for cubicles and robot under a 10 cows scenario); the estimated intercept (β_0) was always higher than zero, and the slope was always less than 45° ($\beta_1<1$).

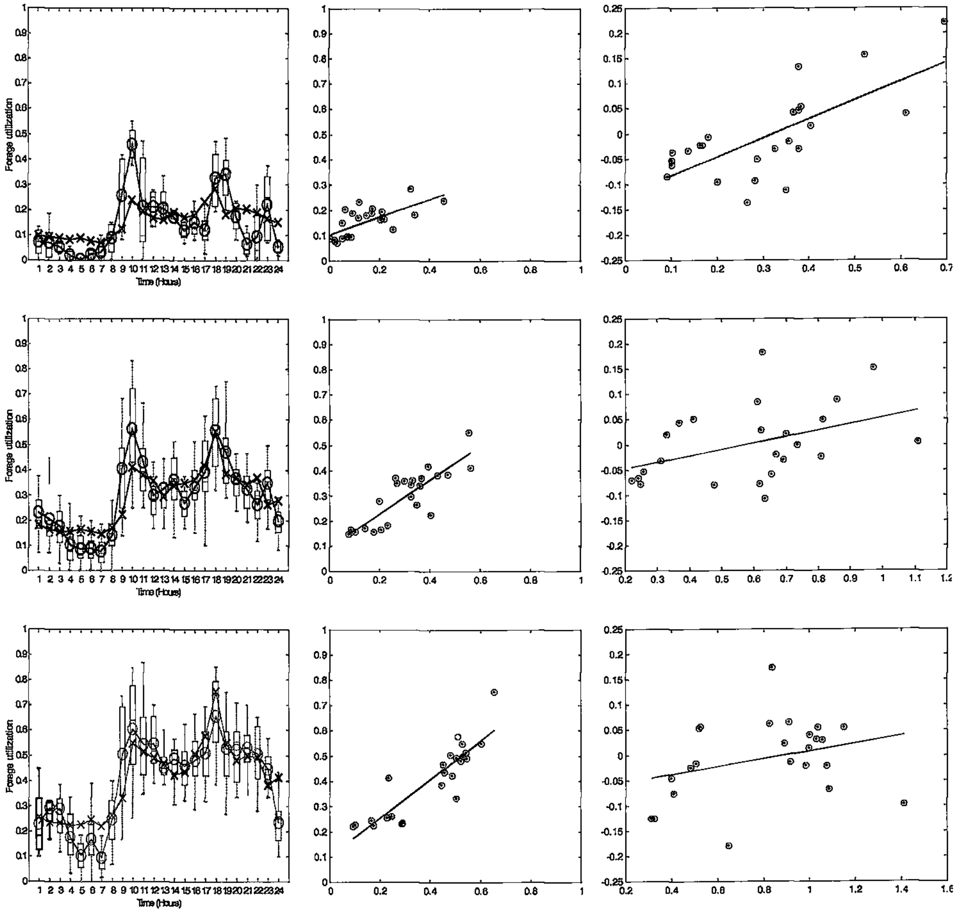

Figure 2. Forage lane utilisation in real and simulated systems with 10 cows (upper row), 20 cows (middle row), 29 cows (lower row): visual analysis (left column), regression analysis (middle column), and Kleijnen's test (right column)

5.2 Kleijnen's test

The results of *Kleijnen's test* suggest that the entire model (all sub-models and scenarios) was valid, with 97.5% confidence (Table 1). Table 1 also suggests that the larger the group of cows, the more valid the model is. For example, cubicle's *F*-statistic is 1.12 for 29 cows and 21.8 for 10 cows.

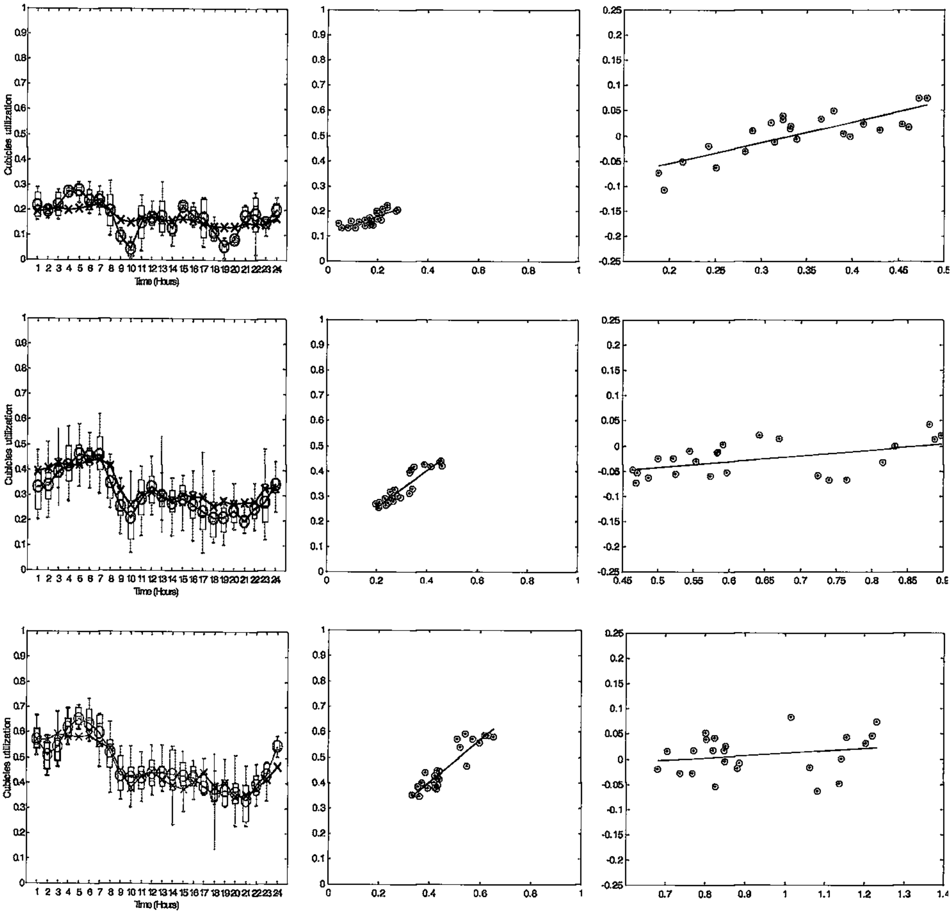

Figure 3. Cubicle utilisation in real and simulated systems with 10 cows (upper row), 20 cows (middle row), 29 cows (lower row): visual analysis (left column), regression analysis (middle column), and Kleijnen test (right column)

Table 1: Statistical validation: traditional regression analysis and Kleijnen's test

Facility	No. of cows	Utilisation		Regression analysis		Kleijnen's test		
		Real	Simulated	Reg. Coef.	F-statistic	Reg. Coef.	F-statistic	
		(mean, STD)	(mean, STD)	(β_o, β_1)		(γ_o, γ_1)	F^{hour}	F^{day}
Cubicles	10	0.17, 0.06	0.17, 0.03	0.11, 0.36	**56.07**	-0.14, 0.41	21.18	34.6
Forage		0.15, 0.11	0.15, 0.06	0.10, 0.35	33.95	-0.12, 0.38	11.09	20.90
Robot		0.17, 0.07	0.16, 0.03	0.17, -0.09	**88.17**	-0.27, 0.85	13.44	3.24
Cubicles	20	0.31, 0.08	0.33, 0.07	0.11, 0.73	20.33	-0.10, 0.12	13.22	5.65
Forage		0.29, 0.14	0.29, 0.11	0.09, 0.67	6.96	-0.07, 0.13	2.31	0.63
Robot		0.32, 0.11	0.34, 0.08	0.24, 0.31	12.89	-0.16, 0.22	1.76	1.12
Cubicles	29	0.47, 0.10	0.46,0.09	0.07, 0.83	2.84	-0.03, 0.05	1.12	2.22
Forage		0.40, 0.17	0.41,0.14	0.10, 0.76	3.86	-0.07, 0.08	1.17	6.44
Robot		0.44, 0.10	0.48, 0.08	0.49, -0.02	19.93	-0.23, 0.21	1.57	7.31
CSF		0.56, 0.15	0.65,0.19	0.22, 0.77	4.74	0.08, -0.14	5.25	12.39

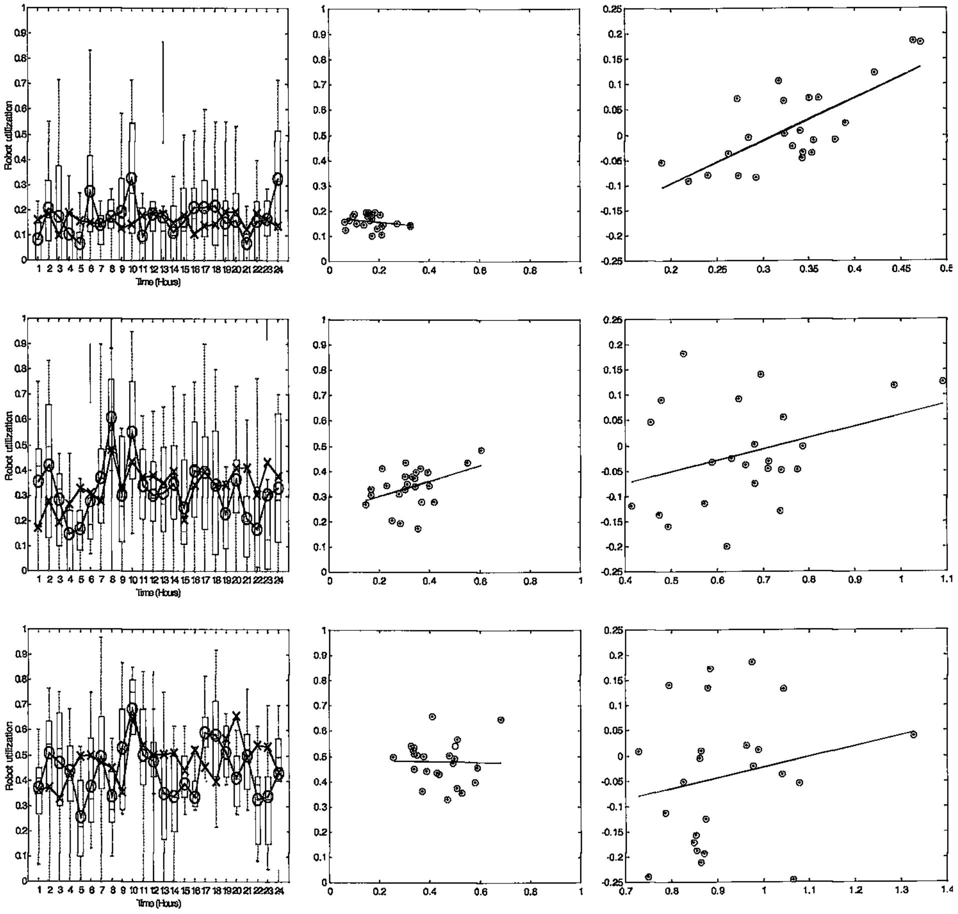

Figure 4. Milking robot utilisation in real and simulated systems with 10 cows (upper row), 20 cows (middle row), 29 cows (lower row): visual analysis (left column), regression analysis (middle column), and Kleijnen test (right column)

6 Discussion

6.1 Utilisation, cost, and animal welfare

In order to compare systems, one has to choose performance measures. We chose *facility utilisation,* which can be measured directly in a real farm, and is a standard statistic in our simulation package. *Utilisation* of a service facility is defined as a function of the number of busy servers[25]. *Utilisation* has economic and animal welfare connotations. For example, a farmer who has paid 200,000 NLG for a robot capable of 200 milkings/day (at maximum practical utilisation, say 85%), but who has only 118 milkings/day (50% utilisation), loses 100,000 NLG directly. In this case, 35% utilisation is equivalent to 100,000 NLG. Utilisation can also be interpreted in animal welfare terms. For example, given a number of cubicles (c) and 90% utilisation (ρ), the arrival rate (λ) can be calculated from the well known queuing relation $\rho=\lambda s/c$ where s is the known service time[14]. Then, also queue length (number of cows waiting to lie down, for food or for milking) and waiting time in the queue can be calculated easily[13].

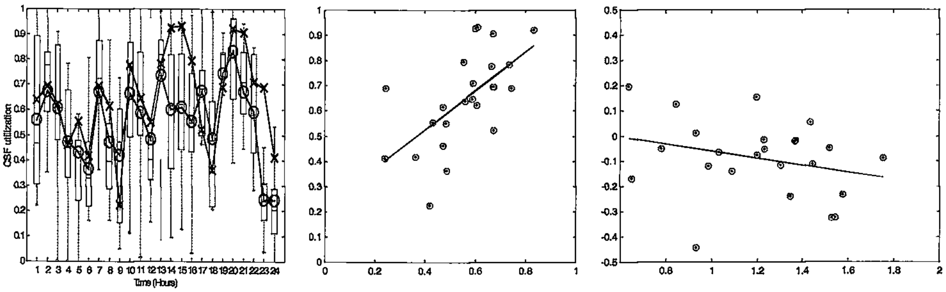

Figure 5. Concentrate self-feeder (CSF); 29 cows: visual analysis (left), regression analysis (middle), and Kleijnen test (right)

6.2 Validation statistics

The *traditional regression analysis*, rejected two scenarios (cubicles and robot with 10 cows), whereas the results of *Kleijnen's test* suggest that the entire model (all scenarios) should be accepted (Table 1). These results agree with the numerical example provided by Kleijnen et al.[21], who stated "the naïve *regression analysis* rejects a valid simulation model substantially more often than the novel test does". According to the pictures of the time series in *Figures* 2-5 (left column, visual analysis), the model is good enough for the purpose of designing robotic barns. Therefore, our judgement can be summed up as 'A picture (visual analysis) is worth more than a thousand statistics', and we conclude that the *traditional regression test* rejected two valid sub-models.

6.3 Herd size and model validity

Table 1 showed that if only ten cows are kept in the barn erroneously the *F-statistic* is higher; consequently the model is less valid for the 10-cow case. We suggest the following explanation. First, when only 10 cows are present, each one has a greater proportional rate or 'weight'. For example, if two cows change location at once, it is a 20% difference in utilisation - a 'jump'. But, in order to reach a 20% difference in utilisation for, say, 100 cows, 20 cows should be relocated at once, which is a rare event in RMB. The social hierarchy also plays a role[3], because the limited floor space, passages, and the gates between facilities are rather narrow. It makes it technically impossible for more than a few cows to exit/enter a facility at once. The fourth reason is the limited number of forage lane positions. The laboratory experiment had a continuous feeding routine, whereas the validation experiment had *twice a day* feedings, and a limited number of feeding positions. More cows in the group make the utilisation line more 'flat', spread equally over the day (see *Fig. 2*) - better matching the laboratory experiment with the continuous feeding. This is why as group size increases, the model's validity improves.

6.4 Model scope and parameters' range

As mentioned above, the optimal layout differs among farms, and it is necessary to update particular parameters for each farm in question. This study validated the model under one farm conditions, but does the validation hold everywhere?. It appears that only two parameter updates (milking time and feeding routine) are sufficient to ensure that the simulation model is valid. However, it should be remembered that the basic principles of semi-forced cow-traffic (CSF in or next to the robot, one-way gate between the CSF and forage yards) and cubicle housing were the same in both experiments - the data source [0], and the validation site. The present paper does not claim to present a 'valid' model when used under completely different housing or management systems (for example, grazing and open cowshed situations such as found in Israel are a different story). Fortunately, the basic principles presented in this study are in common use in RMBs.

7 Conclusion

The simulation model is found to be a valid representation of the real system (97.5% confidence level), so it is useful for research and practical application.

The simulation model requires fewer simplifying assumptions than the previous prototype simulation model[7]. It allows the farmer to integrate all interesting factors into his model, and improves communication between barn operators and designers. Simulation experiments allow joint evaluation of equipment, management practices, farm routine, and layout; they highlight potential design options - before the barn is built.

Having been validated, the simulation model becomes a practical tool for optimising a barn layout. For example, we noticed that the forage lane utilisation of the group of 29 cows reached 90%, so it is not advisable to reduce the number of feeding positions. And cubicle utilisation never exceeded 75%, which suggests that it is feasible to have fewer cubicles than cows (this will probably not adversely affect cow behaviour). A subsequent paper will describe a study in which the valid model was used to estimate the optimal robotic milking barn[26].

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Chapter 6

A case study:
Optimal Facility Allocation in a Robotic Milking Barn

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Abstract

A milking robot is a recent technological development, therefore, there are few precedents and little experience to draw upon when designing robotic milking barns. There is wide diversity among farms, so the optimal layout may vary accordingly. We developed a behavior-based simulation model adjustable for any farmer or site. We improved it by using a metamodel, which allows a global optimum to be found. Under the given condition, of two specific farms, it resulted in the optimal facility allocation: Farm A, 1 robot: 36 forage lane positions, 60 cubicles, and 71 cows; Farm B, 2 robots: 103 forage lane positions, 105 cubicles, and 132 cows. The optimal layouts calculated in this study are unique for each farm's specific characteristics, but the design methodology developed is universally applicable.

Keywords: Robotic milking barn (RMB), Layout design, Optimization, Simulation, Regression Metamodel

1. Introduction

The milking robot is the latest important development in dairy farming (the previous development of comparable importance was the milking machine, invented about half a century ago). The direct and indirect building costs of a new robotic milking barn (RMB) might exceed the cost of a mid-size factory, and its complexity is considerable. However, whereas a factory designer can use systems engineering techniques, this option is not yet available for an RMB designer. The design of a barn is still done by traditional methods and rules of thumb.

Milking robots save labor and affect productivity, cow behavior, feeding routine, and management practices, which all need to be taken into consideration when designing an RMB. Researchers have addressed the complexity of designing an efficient RMB; in relation to the use of the robot and cow traffic through the barn[1-4]. In summary, on a milking parlor oriented farm, the farmer brings the cows to the milking site, whereas in an RMB a cow is expected to arrive voluntarily. This "voluntary" arrival should be supported by the entire system, including barn design, feeding and cow-traffic routines, and management practices. Moreover, the design of a conventional (milking parlor oriented) barn relies on decades of experience, whereas the experience with robotic barns is (virtually) non-existent. Furthermore, there is a wide diversity among farms; each farmer has his existing facilities, building structure, ventilation, preferred feeding routine, and management practices. Therefore, the optimal RMB layout differs among farmers.

An optimal design balances adequate capacity against over-capacity. The optimal layout for a particular farm is unique to that farm, but the methodology developed in this paper is universally applicable, adjustable for any farmer or site. *The aim* of this study is to find an optimal layout for a robotic milking barn, given the farming conditions described below.

2. The concept

Systems engineering and modeling techniques such as queuing theory, Markov chains, and computer simulation have revolutionized the design of factories, telephone networks, banks, supermarkets, etc. However, these techniques have not yet been used to design complete dairy barns. Under continuous robotic milking and feeding, the milking process is spread over the entire day and night, round the clock. By modeling the use of facilities as a stochastic process Halachmi et al.[5,6] showed a way of using systems theories such as queuing and Markov chains to design robotic milking barns. Likewise, behavior-based simulation allows the combined evaluation of equipment, management practices, feeding routine and layout. Simulation improves communication between designers and barn operators, allows the farmer to integrate all relevant factors into his model, and highlights potential design options before the barn is actually built. The main benefit is that before building the farmer gains assurance that the proposed design will actually work and meet his specified demands.

The main limitation of simulation lies in its heuristic character: simulation responses are observed only for the selected input combinations, i.e., there is no proof of the optimality of the solution. In an RMB, a great many input parameters can be distinguished. For instance, farm B (described below, two robots) has about 80,000 input combinations. Obviously, we cannot simulate all of them, therefore, the first step is to select the combination of parameters that are to be simulated in experiments with the behavior-based simulation (BBS). In the simulation literature, this phase is called *design of experiment* (DOE[7]). Regression analysis of the input-output (I/O) data of the simulation gives a metamodel, defined as a model of the underlying simulation experiments, i.e., an approximation of the simulation's I/O transformation. If this transformation happens to be a first or second order polynomial, Kuhn-Tucker conditions are both necessary and sufficient for a global solution point. The extreme points can be found by ordinary algorithms such as projection methods or Simplex[8]. The metamodel allows a global optimum to be found, and the integrated design methodology to be completed.

3. Validation and optimization

We conducted two types of experiments: (i) observation of cow behavior in real (non-simulated), commercial barns, and (ii) computer simulation. The real barn offered insight into RMB operation and provided data for validation. The simulation experiments, through variation in the parameters of interests, provided the data needed to enable the metamodel to find the optimal solution.

3.1 Real systems

In order to draw valid conclusions, typical farms likely to be found in the Netherlands were chosen after consultation with the robot manufacturer (Lely Industries NV).

In both farms, milking frequency was determined by "expected milk quantity" (around 6 litres minimum); in practice this led to four milkings per day (4x) for an above 45 L cow, 3x – above 20 L, and 2x below 20 L. Cluster detaching was done separately for each quarter and so were the real-time measurements: milk yield, electrical conductivity, and milking time. Milk recording was performed once every six weeks, using at least two samples per cow. In the winter automatic cleaning of the robot was done every 9 hours and in the summer every 7 h, with cleaning taking 10-15 minutes. The milk flowed to a single milk tanker (6,200 liter), and was collected once every two days. The six-week experiment was carried out during July and August 1998. Concentrate food was served in the robot, up to 1 kg per milking; the silage, grass, and the rest of the food components were those commonly used in Dutch farms. The forage was distributed in the morning by a mixing wagon, and any remaining by the evening was pushed toward the cows. The layouts are shown in Figure 1.

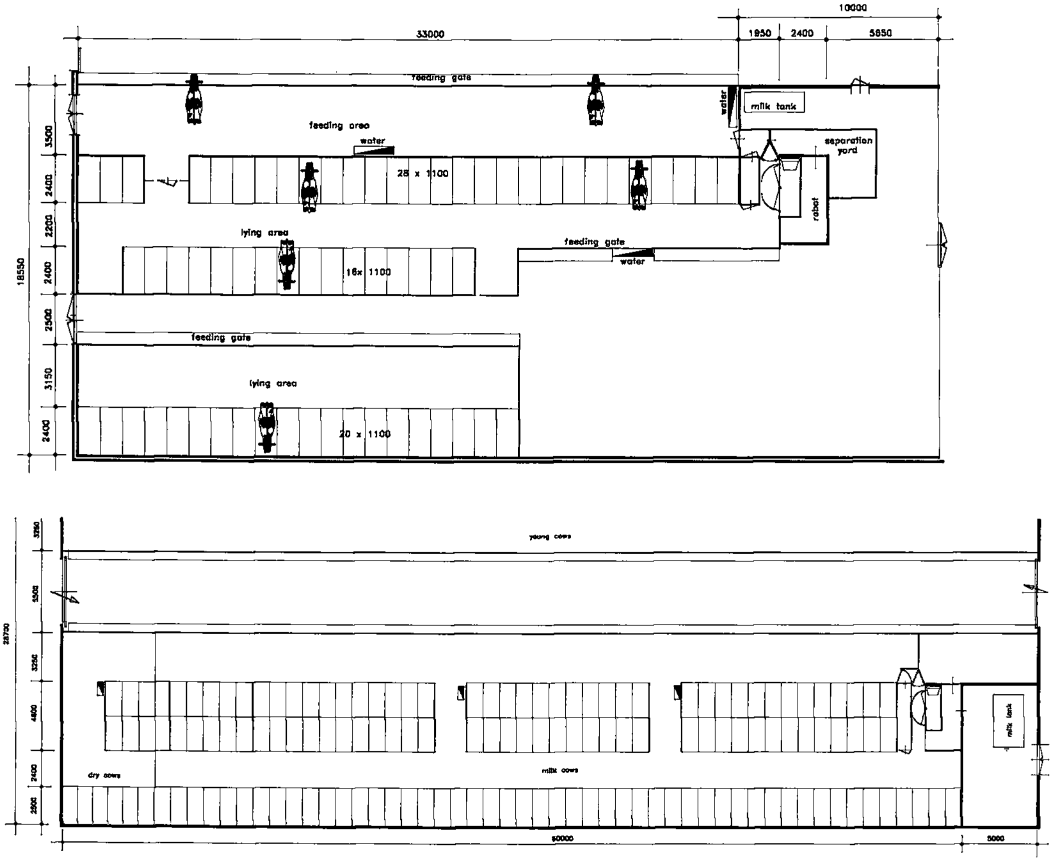


Figure 1. Layouts of the real (non-simulated) barns, farm A (upper drawing), and farm B (lower drawing)

Farm A, a family farm, is located north of Utrecht. According to the farmer, his robot operated continuously and satisfactorily, and the results presented below were collected at the end of the first year. Around 60 cows were milked by the robot, 24 hours a day. The average milk yield per cow was 9,600 kg, with 4.5% fat, 3.55% protein, somatic cell count of 140,000 cells/ml, bacteria count: of 6,000-15,000, during the last year there were only three cases of clinical mastitis. The robot was installed in an existing barn, after reconstruction and refitting. There were about 60 cubicles, enough forage lane positions for almost all the 60 cows, and three water troughs. A one-way gate was located between the forage area and the cubicle area.

Farm B is located north of Amsterdam. An entirely new barn (Figure 1) was especially designed for robotic milking, with the aim of installing more than one robot in the cowshed. There were 142 cubicles, enough forage lane positions for about 110 cows, and three water troughs. At that time, as in the previous farm, only a single Lely robot was installed, which had milked around 60 cows. According to the farmer, the robot operated adequately, and the results presented below were collected at the end of the second year. The average milk yield was 10,000 l per cow, and the fat percentage was 4.35.

3.2 Simulation model

The simulation model was based on empirical data (Halachmi et al.[9]), and has been described and validated in detail elsewhere[10,11]. The main conclusions are summarized below.

The RMB to be optimized had eight input parameters and four response variables, which represent utilization of each facility in the barn. The input parameters were the numbers of cows, cubicles, robots, forage-lane positions and water troughs, together with the type of barn (layout drawing), the cow-traffic routine (that determines transition probabilities between facilities), and the farmer's preferences for feeding times, maintenance and treatment routines. The robot's "service time" varied among farms and was updated in the BBS software. All other variables remained the same as in Halachmi[10]. The simulation output consisted of (i) facility utilization, measured over 30 days of activity for each facility in the barn, i.e., robot, cubicles, forage lane, water troughs; and (ii) queue length, i.e., the number of cows waiting for an unavailable facility. Although the BBS software might be extended to cover more responses, e.g., waiting time (in minutes) - in the present study we employed only facility utilization and queue length.

The robotic milking barn, including its facilities, operators, and cows was modeled with a stochastic, discrete-event simulation. The simulation model was based on a modular approach with the system (barn) being broken down into five modules, whose interactions formed the barn behavior. These modules are the barn facilities: the milking robot, the concentrate feeder, the forage lane, the water troughs, and the cubicles. In a facility *(module)*, there are parallel *resources*, which have service times that depend on the cow's individual attributes.

A barn was modeled by using *process orientation*, in which a *process* denotes the sequence of operations or activities through which a cow progresses. For example, in the robot, a process may consist of a cow's entering the stall, followed by feeding, cluster attachment, milking, cluster detachment, and departure.

If a *resource* is empty when a cow arrives, the cow stays there during its '*service time*', measured in minutes; otherwise, the cow is routed to a queue in front of the facility.

The simulation programming language was Arena[12]. We also used CAD software, namely Cadkey[13]. In order to combine the layout drawing of the barn with the simulation kernel, a DXF file containing the scale drawing of the given barn was loaded into the simulation software. A DXF file can be created by other CAD software also (e.g., Autocad[14]). The *statistics*, which keep track of the state of the barn, were automatically transferred to Matlab[15] for further analysis, multiple regression, and linear programming.

In the animation, vivid colors indicate a cow's state: a green cow is in "working mode", i.e., occupying a facility, eating, being milked, or resting; a blue cow is in a "transit mode", i.e., either walking between facilities or idle. A queuing cow's color is changed to red. The simulated barn B is presented in Figure 2.

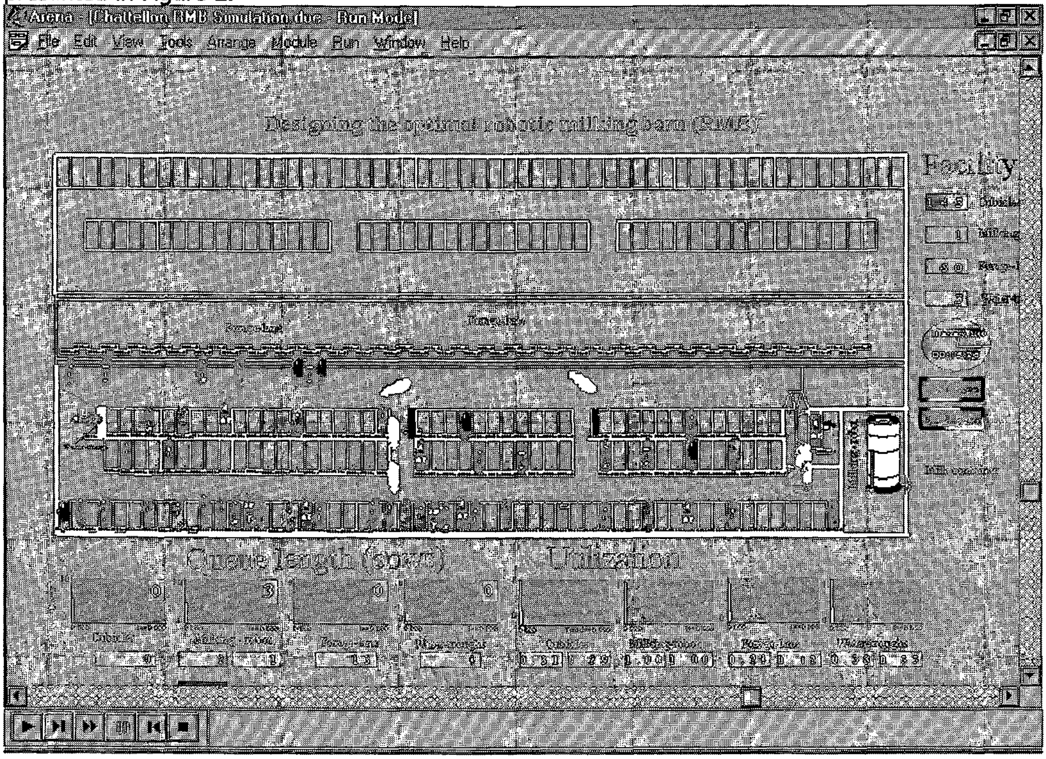


Figure 2. The real farm B, and the user interface of the behaviour based simulation (BBS) model

The layout is shown at the center of the computer screen. During the simulation run, the cows, facilities, tractor, worker and milk-tanker are all shown moving as if in real life, though accelerated in speed. It can be seen that three cows are in front of the robot waiting in a virtual queue, while one cow is being milked in the robot. The clock at the right side of the screen shows the simulated time. Next to it, we see the number of cows in the barn (60), and the average milkings per cow per day (MCD). A utilization graph for each facility and queue length are at the bottom of the screen. The digit at the top right-hand corner of each graph is the current value, while the graph shows the historical values during the preceding 540 minutes.

3.3 Statistical validation

The general validity of the BBS model has been discussed and proved elsewhere[11]. However, site-dependent parameters (such as feeding routine and other farmer preferences) vary between farms. Therefore, we re-evaluated the validity of the model for the conditions of farm A and farm B. We compared real-world observations and simulation output data, by using the paired-t approach as recommended by Law and Kelton[16] (section 5.6). The following observations are given in Table 1: R_i^A was the average utilization of the robot in the real barn A, during day i; R_i^B was the average utilization of the robot in the real barn B, and S_i^A and S_i^B were the output data from the corresponding simulation models. Let W=R-S, and n=30 days. Then the 95% confidence interval of W can be calculated as $\bar{W} \pm t_{29,0.95}\sqrt{Var(W)}$ (Eq.1). If the interval did not contain zero, the difference between the real barn and the simulation model was statistically significant. Table 1 shows that the simulation model was a valid representation of reality, and therefore it could be used in the metamodel phases.

Table 1. Model validation: comparing experiments with real and simulated barns

Day	Farm A utilization Real (R^A)	Simulation (S^A)	Farm B utilization Real (R^B)	Simulation (S^B)
1	0.78	0.77	0.79	0.86
2	0.76	0.75	0.77	0.78
3	0.79	0.69	0.86	0.80
⋮	⋮			
27	0.80	0.74	0.80	0.84
28	0.80	0.75	0.82	0.78
29	0.80	0.69	0.83	0.85
30	0.83	0.72		
⋮	⋮	⋮		
42	0.82	0.78		
43	0.79	0.77		
44	0.81	0.71		
mean:	0.78	0.73	0.81	0.79
STD:	0.027	0.036	0.025	0.039
95% Conf. Interval (Eq.1)	[-0.03, + 0.14]		[-0.06, +0.10]	

3.4 Design of experiment, metamodel and optimization

Design of experiments (DOE) can be defined as the selection of the combinations of input factor values that will actually be simulated. The goal is to gain insight into the simulation model behavior while observing relatively few factor combinations. In the first *DOE* step, the feasible range of each parameter (boundary) was determined through "playing-around" (also called exploration analysis) with the BBS software. Changing one factor at a time, we reduced the number of allocated positions, until almost 100% utilization was reached, and the maximum facility allocation was limited by the number of cows in the herd. An additional simulated point was the middle range of each parameter. After a few such "runs" we realized that three water troughs were enough; having fewer would not be practicable, as these are a relatively cheap facility and very important to high milk yield. We recommend that at least three troughs be installed, one in each section of the barn (this follows the recommendations given by Bickert *et al.*[17]). Therefore, in all our runs we simulated three water troughs. The number of robots determines the layout, thus a new layout drawing, and thus, a new complete set of input factor combinations are needed for each change. Therefore, water troughs and robots were kept constant, namely three water troughs, and one robot in farm A and two robots in farm B. Finally, it appeared that the farm with two robots needs between 20 and 120 forage lane positions and cubicles, and between 60 and 120 cows.

After fixing the factor boundaries, we used a *full factorial design*[18] in the second step. This consisted of all possible combinations of the three factor levels, comprising 27 (3x3x3) input factor combinations: forage lane positions =[20,70,120], cubicles =[20,70,120], and number of cows=[60,70,120]. Later, after looking at the simulation results, we added one further run: [150 cows, 120 forage positions, and 120 cubicles]. A simulation run of one combination took only 1½ minutes on a 200 MHz PC.

At this point it is convenient to introduce further terminology; in the following list, an uppercase letter denotes a matrix; a lowercase letter indicates a column vector:

y_i= simulation response (namely, facility utilization) of factor combination i (i=1,...,28)

$X_{i,j}$ = values of input factor j in combination i. Input factor j (j=1,...,3) represent numbers of cows (j=1), cubicles (j=2), and forage-lane positions (j=3).

b column vector (3x1) containing the regression coefficients, namely, b_{robot}, $b_{cubicles}$ and b_{forage} associated with the robot, cubicles, and forage lane respectively.

e is the regression fitting error after the least squares fit of y on X.

x^*_i = the optimal values of x_i (3x1 column vector), namely the number of cows (x_1), the number of cubicles (x_2), and the number of forage lane positions (x_3).

In the third step we calculated a multiple linear regression, namely the first-degree polynomial y=Xb+e. The resulting R^2 was higher than 88% for all three facilities (robot, cubicles, forage lane). Therefore, fitting the second-degree polynomial was not necessary. The output of this step consisted of the regression coefficients: b_{robot} , $b_{cubicles}$, b_{forage}.

In the fourth step we ran the linear programming (LP) model; its goal was to estimate the optimum values (x^*_i) for the quantitative inputs of the system (x_1, x_2, and x_3). We formulated the design constraints as follows: robot utilization $\leq$ 0.9, cubicles utilization $\leq$ 0.95, forage lane utilization ≤ 0.2, at least 70% of the cows able to lie down in the cubicles simultaneously, and at least 50% of the cows able to eat forage simultaneously. Under these constraints we would like to hold the maximum number of cows. This leads to the following LP problem:

$$
\begin{aligned}
&\textit{min.}\ \ -x_1\\
&\text{s.t.}\ \begin{pmatrix} b^t{}_{robot} \\ b^t{}_{cubicles} \\ b^t{}_{forage} \\ 0.7 & -1 & 0 \\ 0.5 & 0 & -1 \\ -1 & 0 & 1 \\ 0 & -1 & 1 \end{pmatrix} x^* \leq \begin{pmatrix} 0.9 \\ 0.95 \\ 0.2 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \text{(Eq. 2)}\\
&x_i^* \geq 0
\end{aligned}
$$

For example, the first constrain, $b_{1\,robot}X_1+b_{2\,robot}X_2+b_{3\,robot}X_3$ should not exceed or equal to 90% robot utilization. And the fourth constrain ($0.7X_1 \leq X_2$) means: "at least 70% of the cows are able to lie down in the cubicles simultaneously"; the fifth constrain ($0.5X_1 \leq X_3$) means: "at least 50% of the cows are able to attend forage simultaneously". Finally, the number of cows is bigger than the number of forage positions ($X_3 \leq X_1$, the 6th constraint), and there are more cubicles than forage positions ($X_3 \leq X_2$, the 7th constraint). Obviously, for further research, constraints can be chosen differently for each farm under-study, after consultation with the farmers and the robot manufacturer.

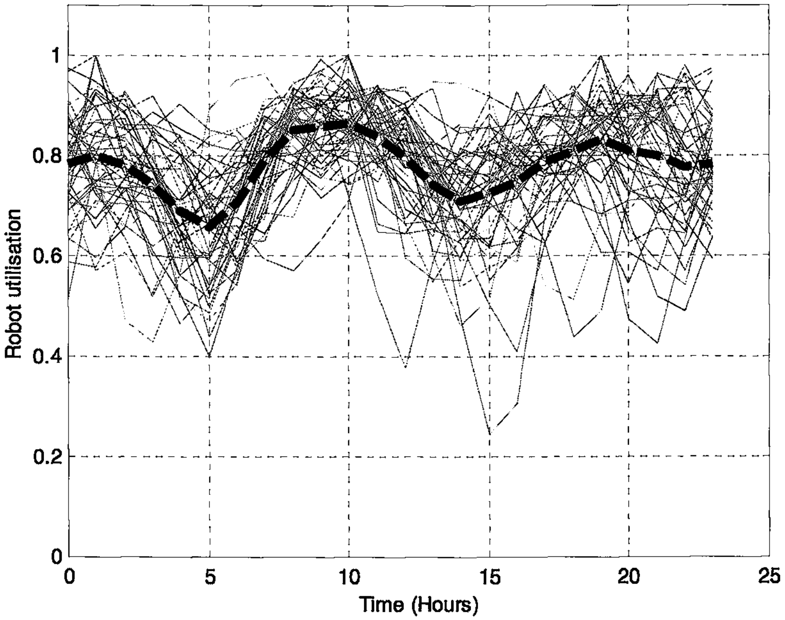
Eq. 2 are convex functions, and consequently Kuhn-Tucker conditions are necessary and sufficient for global optimality. Matlab solves this LP problem by a projection method, which is a variation on the well-known Simplex method[8].

4. Results

We present two types of results: measurements in commercial RMBs, and the optimal solution calculated using metamodel techniques.

The average utilization of the robot in the real barns is illustrated in Figure 3. It can be seen that, in general, practical utilization was around 80%, throughout the entire experimental period. This means that the robot's load pressure was rather high, and the robot reliability met the demands. Connection failures affected 1.252% of the visits, comprising 1.004% of the robot's time. On only a few days was the utilization lower than 50%, which meant that the robot was not working for a period of half an hour, perhaps because of a technical problem or simply because cows had not arrived. The lower points in the utilization cycle, around 5 a.m. and 3 p.m., were the results of the robot cleaning time (cleaning takes about 15 minutes; at that time the robot does not operate, so its maximum utilization per hour is only 75%). Figure 4 presents the real (non-simulated) milking time by the robot (milking duration, minutes per single milking). It can be seen that the milkings in farm B took a little longer, which is related to the higher milk yield in farm B.

This result agrees with the findings of Dzidic[19], who investigated the correlation among robot milking time, milk yield, and other parameters.



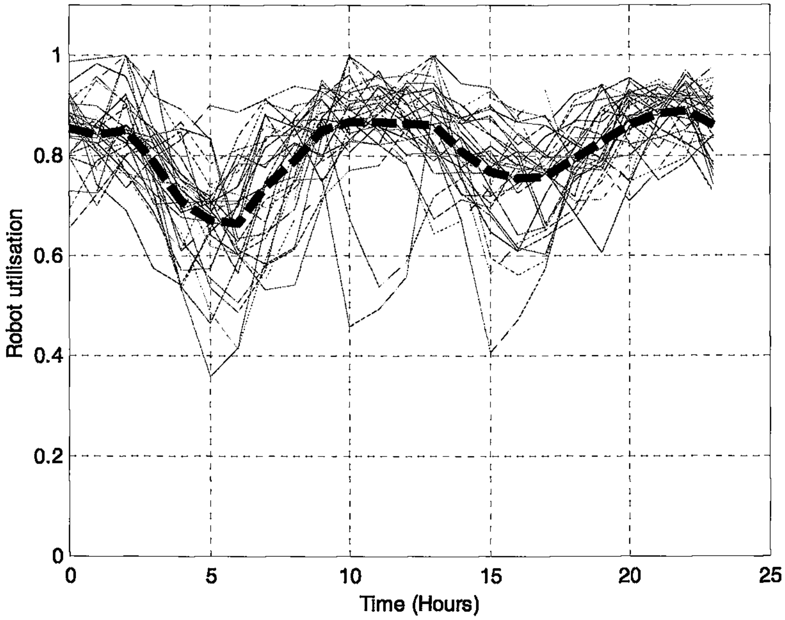
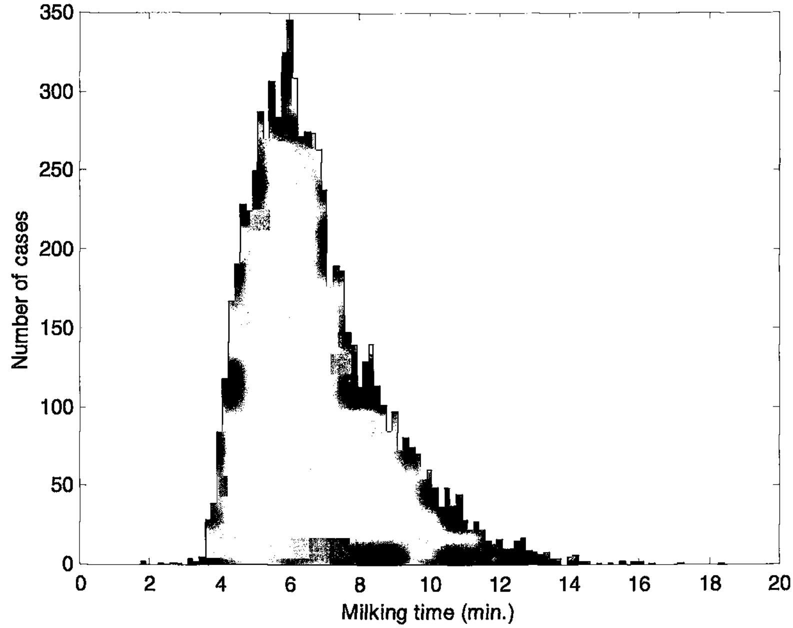


Figure 3 Real (non-simulated) utilization: farm A (upper figure), and farm B (lower figure). Each line represents one day in the experiment and the dash bold line represents the average for the entire period.



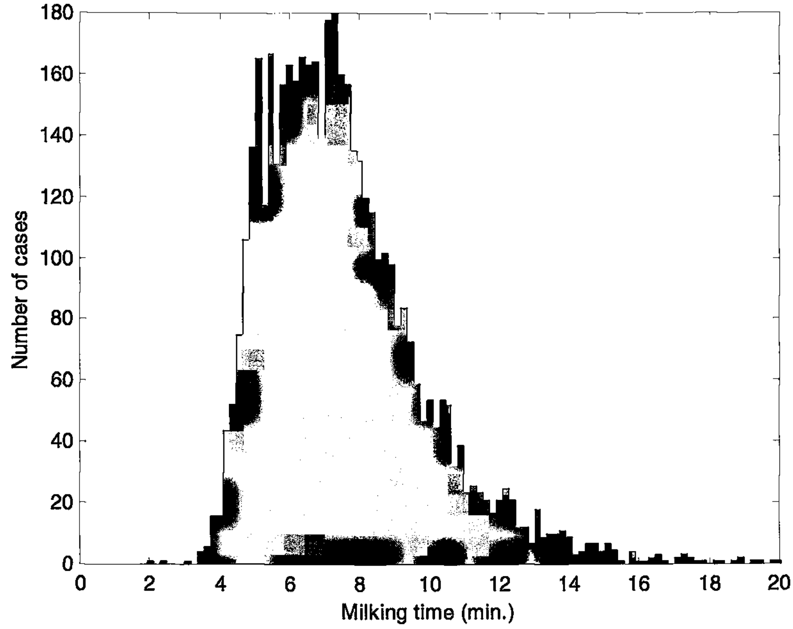


Figure 4. Milking time distribution: farm A (upper figure, mean=6.76 min; std=1.92) and farm B (mean=7.52 min; std=2.29 min).

The regression coefficients associated with the utilization of forage lane, cubicles, water troughs and robots respectively, that were obtained in the metamodel phase (for two robots) are:

b_{forage} = [0.0027635 -0.0041018 0.0028029]'

$b_{cubicles}$ = [0.0066010 0.0008334 -0.0000343]'

b_{water} = [0.0027133 0.0000967 0.0006888]'

b_{robot} = [0.0062033 0.0000327 0.0003786]'

where, R^2 was higher than 86% for all cases. By substituting these regression coefficients and solving the linear programming problem in Eq. 2, we estimated the optimal solution:

x^*_i(farm B, two robots) = 131.434 cows; 102.659 forage lane positions; and 92.0036 cubicles, which we round upward. Obviously, this optimal solution satisfied the constraints:

Robot util. = $b'_{robot} x^* = 0.85$ (≤ 0.9, constr. 1)

Cubicle util. = $b'_{cubicles} x^* = 0.95$ (≤ 0.95, constr. 2).

Forage util. = $b'_{forage} x^* = 0.2$ (≤ 0.2, constr. 3),

Compared with the current situation of farm B (Fig. 1), the proposed allocation saves eight forage lane positions, and 50 cubicles, without impairing robot utilization. However, additional simulation experiments (fine-tuning of the metamodel's solution) suggested that the proper number is 105 cubicles.

Given the same constraints, the optimal allocation that was obtained for an RMB containing one robot is:

x^*_i (farm A, one robot) =65 cows; 60 forage lane positions; 64 cubicles.

Robot util. = 0.83 ≤ 0.9; (constr. 1)

Cubicle util. =0.95 ≤ 0.95; (constr. 2)

Forage util. =0.2 ≤ 0.2; (constr. 3)

When we increase the forage constraint from 20% to 90% utilization, we get more cows and less space:

x^*_i=71 cows; 36 forage pos.; 60 cubi pos.

subject to: Robot util. (constr. 1)= 0.900 ≤ 0.9

Cubi util. (constr. 2)= 0.950 ≤ 0.95

Forage util. (constr. 3)= 0.411 ≤ 0.9.

Compared with the current situation (see farm A, Fig.1), the proposed allocation offers a reduction of 30 forage positions, about the same number of cubicles, and an additional 10 cows, without impairing robot and cubicles utilization.

Figure 5 shows the trade-off between queue length and robot utilization. It shows the simulation results around the optimal solution. For one robot (left-hand side), it can be seen that if there are more than 65 cows in the barn, the facility idle time (1-utilization) is lower than 15% and queue is longer than five waiting cows. For 70 cows the robot idle time is 10%, and the queue length is eight cows. For two robots (right-hand side), if there are about 130 cows in the barn, the idle time is lower than 15% and the queue is longer than five cows.

In all the cases, the optimization was terminated successfully.

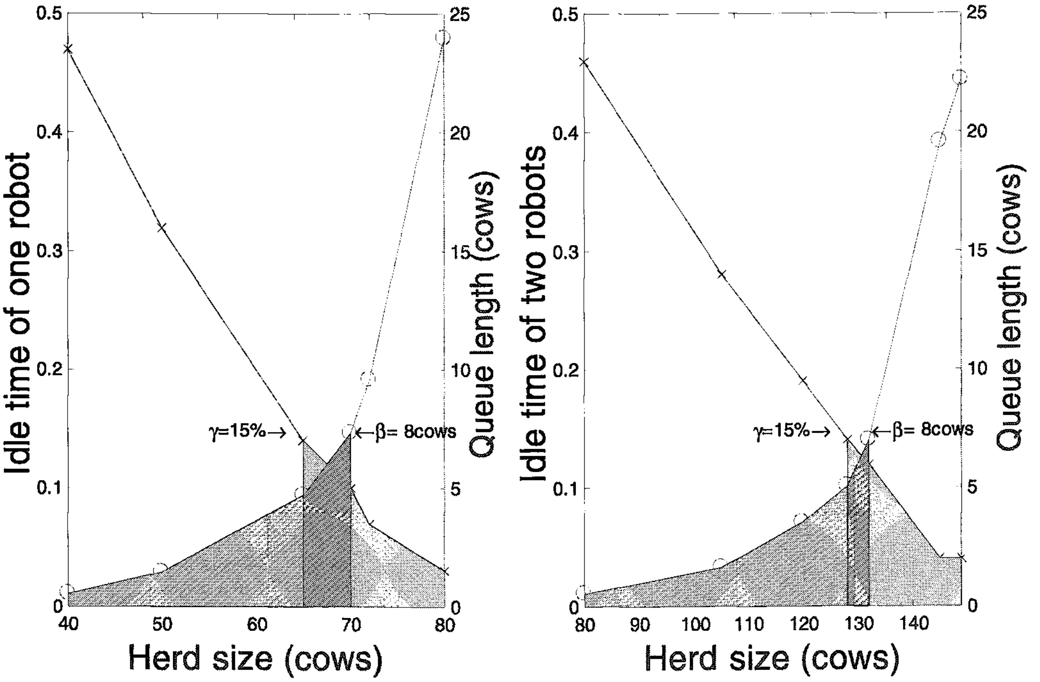


Figure 5. The system performance in terms of robot 'idle-time ratio' (left-side Y-axis, 'x'-marked line) and cow queue length (right-side Y-axis, 'o'-marked line) as function of number of cows in the herd. Using a fixed number of facility allocations (left picture: farm B, 1 robot, 60 forage lane positions, 64 cubicles; right picture: farm A, 2 robots, 103 forage positions, 105 cubicles). The constraint levels are: 'idle time ratio' ≤ 15% and 'queue length' ≤ 8 cows.

5. Discussion

5.1 The link between utilization, cost, and animal welfare

As the measure of performance, we chose *facility utilization,* which can be measured directly in a real farm, and is a standard statistic in our simulation package. *Utilization* is important both economically and in terms of animal welfare. For example, if a farmer paid 200,000 NLG for a robot capable of 200 milkings per day (at maximum practical utilization of, say 85%), but that farmer achieved only 118 milkings per day (50% utilization), there would be a direct loss of 100,000 NLG. In this case, 35% utilization equals 100,000 NLG, i.e., the ratio is about 2,850 NLG per 1% utilization. Utilization can also be interpreted in animal welfare terms such as queue length in front of a facility (how many cows are waiting to lie down, for food or to be milked ?) and waiting time in the queue can also be easily calculated[5]. Obviously if the facility utilization is too high, a long queue might occur.

5.2 Does our optimal solution hold elsewhere ?

It seems that adjusting only three parameters (milking time, cow traffic, and feeding routines) is sufficient to provide a valid simulation model. However, one should keep in mind that the basic principles of cow traffic and cubicle housing were maintained in both experiments: the data source[9,10], the validation sites[11], and the farm in question. The present paper makes no claim to validity of our optimal solution under completely different housing or management principles (for example, an open cowshed such as is used in Israel). Fortunately, the basic principles used in this study are in common use in today's RMBs.

6. Conclusion

A behaviour-based simulation model, together with metamodel and optimisation techniques that formed an integrated design methodology for robotic milking barns was developed. The design focused on optimal facility allocation and its relation with herd size, feeding routine, and management practices. The metamodel allowed a global optimum to be found.

Using the new design methodology and rigid design specifications, formulated in terms of mathematical constraints, suggests that if this design methodology had been developed previously, and if it had been applied prior to installation, the savings in building costs could have been significant. Farm A could have saved 30 forage positions and added 10 cows, and farm B could have saved eight forage positions and 50 cubicles, while keeping the same level of robot performance and animal welfare.

Operational research into facility usage of two commercial RMBs showed that robot utilization was rather high, and that robot reliability met the practical requirements with very little technical failure and maintenance.

The simulation model is a valid representation of reality (95% confidence level), so it is useful for research as well as practical design and marketing.

Given the conditions mentioned above, the following optimal facility allocations were determined: (farm B, 2 robots): 103 forage lane positions, 105 cubicles and 132 cows; and (farm A, 1 robot): 36 forage position, 60 cubicles, and 71 cows.

The optimal layout calculated in this study is uniquely appropriate for a specific farmer, but the methodology developed in this paper is universally applicable; the parameters can be adjusted to every farmer, site or milking robot.

7. Acknowledgements

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Chapter 7

Discussion and conclusions

Outline

It is easy to design a barn which always has enough internal space - simply by making it too big; but this is certainly a waste of money. The art is to design a building that balances the cost of under capacity against that of over capacity. Such a balance will vary over time (because of demand variations during the day as well as long term management strategy with the equipment used, and according to the farmer's preference (or personality) and management attitudes, and the interrelation among these factors. Therefore, it appears that designing a robotic milking barn (RMB) is a rather complex problem. In order to discuss it, this chapter is organised as follows[1]: 1) generalisations drawn from observations, and which might be exploited as design principles, 2) limitations of the model, 3) agreement with and differences from previously published work, 4) unfulfilled expectations and suggestions for further research, 5) possible practical applications, and 6) conclusions.

1. Generalisations derived from observations

This subchapter is organised as follows: the main principles derived from the experiments are discussed in section 1.1. Section 1.2 presents the generalisations derived by developing the queuing network algorithm (analytical model), and section 1.3 presents the generalisations derived by using this analytical model. Section 1.4 generalises the results of developing a behaviour-based simulation model. Section 1.5 discusses the generalisations derived from the validation experiments. Finally, section 1.6 discusses the generalisations drawn from the optimisation phase.

1.1 Results of operational research in facility usage

With respect to a robotic milking barn (RMB) with cows fed continuously around the clock and having unlimited facility allocation (the conditions described in Chapter 1), it can be generalised that:

a) Facility usage in the RMB is a continuous-time stochastic process, spread over 24 hours per day. The cows' entries (arrival times) to any of the facilities, and the durations of their visits (service time) to the forage lane and water troughs can be represented as exponential distributions. The service times in the milking robot and concentrate self-feeder (CSF) fit two mixed distributions, distinguished by the milk yield and the amount of concentrates consumed during each visit (robot: Normal and Weibull; CSF: Normal and Log-Normal). The service time in the cubicles can be derived from Beta and Weibull distributions.

b) In our experiment, the interrelation among the several barn facilities can be formulated in terms of a transition probability matrix, which shows that in 90% of the cases, a CSF visit follows a robot visit. This suggests that the main reason cows visit a milking stall is their expectation of receiving concentrates and, therefore, that the CSF is an effective forcing device (either stand-alone or in a milking stall) that might be exploited as the sole tool for forcing the cows into a particular traffic routine.

c) The transition matrix indicates that there are widespread movements between the forage lane and the cubicles, and between the forage and water troughs. If a forced routine prevented these movements, it might impair animal welfare and feed intake.

With respect to a robotic milking barn with cows fed twice a day and a varying number of cows (the conditions described in Chapter 5), it can be generalised that:

d) Forage feeding times dominated the time pattern of the cows' feeding behaviour, and influenced the entire system performance. At these times, forage lane utilisation reached 90%, only a few cows were in the cubicles, and robot utilisation was relatively high. This shows that: 1) the farmer's feeding routine should be an integral part of the model; and 2) if all the cows eat at the same time, it is inadvisable to reduce the number of feeding positions.

e) The observed cubicle occupation never exceeded 75%, which suggests that it would be feasible to have fewer cubicles than cows without adversely affecting animal behaviour and welfare.

The operational research in the two commercial RMBs (Chapter 6) showed that:

f) Robot utilisation in the two commercial RMBs was rather high (about 85% throughout the 24 hours), and its attachment performance met practical requirements (failure affected 1.25% of the visits and occupied 1.004% of the robot's time). This reveals that robotic milking has progressed from initial development to having sufficient reliability needed for mass production.

The operational research into use of the RMB facility and quantification of animal behaviour provided the main theme of this thesis: it opened the way to the use of system theories and mathematical models (such as QN, MC, and CS) in the design of robotic milking barns.

1.2 Developing the queuing network algorithm (analytical model)

The robotic barn resembles a queuing network, i.e., it contains a series of service facilities (robots, CSFs, forage lane positions, cubicles, water troughs, etc.), at some or all of which, cows must receive service. The cows determine the linkages among the various facilities, with respect to their use: after having been serviced in facility i, the cow proceeds to facility j (i.e., a transition matrix is applicable). However, the queuing network model (QN, Chapter 2) cannot be solved exactly, but the arrival theorem and mean-value analysis (MVA) produced a good approximation (the accuracy was 99.9-99.5% for the utilisation and 99-98% for the mean waiting time). This suggests that if farm conditions are somewhat similar to those described in Chapter 1, the QN techniques could form a useful design tool for optimising facility allocation. Otherwise, the QN model provides the initial design point from which the design may be heuristically optimised by means of simulation techniques.

1.3 Using the analytical models

With the farm described in Chapter 3, if the animal-welfare aspiration levels were 1) queue length, β smaller than 1 cow, 2) waiting time in the queue, α smaller than 1½ min, and 3) robot utilisation, γ above 70%, the model predicted that the herd should be larger than 50 cows (to meet the required γ level) but should not exceed 60 cows (to meet animal-welfare aspiration levels: α and β). Thus, the herd should comprise 50-60 cows. In the case of a second farm, as described in Chapter 3, the configuration consisting of 6 CSFs, 27 forage lane positions, 115 cubicles, and a four stall milking robot is enough for up to 140 cows; with fewer than 120 cows it results in inefficient usage of the facilities (long idle times). The average robot idle time is 25%, the average queue length is three waiting cows, and each cow waits on average, 3 minutes. These examples suggest that although queuing network techniques for analysing design of livestock housing still generally suffer from an overabundance of simplifying assumptions, these techniques can, never the less be useful for designing RMBs to meet both economic and animal welfare needs. On the theoretical level, the principal benefit is that defining "cow-friendly" values of α and β opens the way for designing barns based on animal welfare requirements. It also suggests a direction towards defining "ISO" standards for animal welfare.

1.4 The behaviour-based simulation (BBS) model

The BBS forms an interface between the eventual user and the mathematical level of the model; it requires fewer simplifying assumptions than the network model, and improves communication between barn operators and designers (Chapter 4). The BBS enables a designer to optimise facility allocation in a barn, because an initial design can be heuristically fine-tuned to produce a balanced system, specific to the farm in question, within a reasonable programming time. For example, use of the BBS with the animal-welfare aspiration levels chosen for the specific farm described in Chapter 4 resulted in suggestions the following: a) Reductions of about 70% in forage-lane positions and of about 10% in the number of cubicles may not impair animal welfare; there would be little waiting time in each queue, and important resources would be available reasonably often. b) The robot waiting area, i.e., the floor space for queuing should have a capacity of eight cows (to accommodate the longest queue, during short peak times). c) To match its peak demand, the CSF waiting area should have a capacity of six cows. If a simulation study had not been performed, and if a bottleneck in cow traffic had been discovered after installation, the cost of retrofitting extra capacity could have been significant. Besides these quantitative benefits, application of the BBS provides qualitative benefits: 1) the animation of the layout allows a range of personnel unfamiliar with milking robots to appreciate how the new RMB system would operate, 2) the farmer can gain confidence, before building, that the proposed design would actually meet his specified requirements, 3) authorities can gain the assurance before a facility is built that a proposed design would meet specific animal welfare requirements.

1.5 Validation

The simulation model proved to be a valid representation of the real system (97.5% confidence level) under commercially feasible conditions described in Chapter 5. Varying the parameter of the number of cows in the herd and investigating its influence on model performance suggested that the simulation represented the real barn quite well (Chapter 5). However, the larger the group of cows, the greater was the validity of the model, and for a very small group (10 cows), the simulation did not adequately follow feeding time events in the real barn. This may have been because the data source had a continuous feeding routine while the validation experiment used twice daily feedings. In practice, a 10-cow scenario would be not a practical RMB situation, but this finding emphasises the necessity for proper data sources.

After visual analysis, choosing the right statistics is of crucial importance: regression analysis rejected two valid sub-models (cubicles and robot with 10 cows), whereas the results of Kleijnen's test, face validity, and visual analysis suggested that the entire model (and all its scenarios) was valid for the purpose of designing robotic barns. Having been validated, the simulation model becomes useful for research and forms a practical tool for optimising a barn layout.

1.6 Optimisation

An optimal design balances adequate facility capacity against over capacity. But the actual capacity of each facility (such as robot, forage lane, concentrate feeder) depends on the cows' access (and obviously, on the potential capacity: mechanical and attachment performance, reliability, etc). Cow access depends on animal behaviour, barn design, farm routine and management practices; and consideration of all of these together suggests that we are dealing with a quite complex system... An optimal design should balance animal welfare, on the one hand, against facility utilisation, on the other hand. If the idle-time fraction of a facility (one minus utilisation) is small, the cost per cow is lower, but the cow queue length is longer, which might impair animal welfare and might thereby reduce long-term cow performance and health. Therefore, the two conflicting forces are the economic need for high facility utilisation against animal welfare. The BBS assesses animal welfare in terms of queue length and waiting time for an unavailable facility. Other possible criteria, such as restless or aggressive behaviour may be topics for future research. Further difficulties arise from the fact that computer simulation cannot (mathematically) prove that an absolute optimum has been found: simulation responses are obtained only for selected input combinations. However, a metamodel enabled a absolute optimum to be found and thus enabled the BBS to be improved. As a numerical example, appropriate for the commercial RMB conditions specified in Chapter 6, the following optimal facility allocations were determined: two robots, three water troughs, 103 forage lane positions and 92 cubicles, for 132 cows. For the second farm, the allocations, were: one robot, 36 forage positions and 60 cubicles for 71 cows. By application of the newly developed design methodology Farm A would have saved 30 forage positions and added 10 cows, and farm B would have saved eight forage positions and 50 cubicles, while maintaining the same level of robot performance and animal welfare.

The optimal layout calculated is for two specific farms, but the results show that the new methodology offers the potential to be universally applicable, adjustable to any farmer or site.

2. Agreement with and differences from previously published work

The semi-forced traffic routine described in this thesis (access to the CSF only via the robot) differs from previous systems in this area: Sonck[2] and Uetake[3] described human-controlled cow traffic, others[4-7] described selection units and one-way traffic, and Hogeveen[8] compared one-way and free cow traffic. For robots in their early development stages and during a start-up period in each new RMB, a forced routine would fit the requirements[2-7]. However, since robots have reached a certain level of technical maturity, a free or semi forced routine may be more appropriate. The semi-forced traffic is in agreement with the work by Ketelaar-de Lauwere[9].

In Chapter 1 we described a 'full-freedom-to-choose' experiment, performed in order to acquire animal behaviour data that were unconstrained by a specific barn layout. However, if our 'unconstrained behaviour data' may have some local constraints, it may not fit everywhere. The author did not find any published description of an experiment performed with an extremely loose RMB, with considerable excess capacity allocated to the facilities in order to investigate cows' preferences when they have full freedom to choose. And in general, he did not find published data describing cow behaviour that was completely independent of the ban layout in which the experiment was performed. Thus, it is recommended (in future research) to explore this type of experiment under a variety of conditions and to define the boundary of its validity.

The optimal forage lane length calculated for the two RMB examples (in Chapter 6) differs from the current recommendations[10]. Also, the smaller number of cubicles in relation to the number of cows is not recommended elsewhere[10,11], because the current recommendation are based on milking parlour situations, in which all the cows are driven in groups to and from the milking parlour.

The finding of feeding time peaks that dominate cow behaviour at the feeding lane is consistent with previous publications[12,13], and suggests that the feeding regime is an essential part of the BBS model, which should be adjusted for each individual farm.

The high reliability (around 85% utilisation throughout the 24 hours, attachment failure rate of 1.25%, occupying 1.00% of the robot's time) of the robots, as observed in the two commercial RMBs differs from the finding reported for early milking robots[2-4], and suggests that robot technology has reached a level of maturity.

The use of simulation techniques in RMB design recalls the work of two researchers in particular. The first of these, Van Elderen[14] showed that simulation is a useful tool for investigation of the influence of herd size, milk yield per milking, cow behaviour and selection units on the performance of the robot. Secondly, Sonck[15] concluded that simulation is a powerful tool for labour planning. Others[16-22] have developed simulation models of milking parlours (non RMB). Gonyou[23] and Stricklin[24] proposed 'animats', computer simulated artificial animals. These authors[14-24], however, simulated the operation of a single facility in a barn, whereas the present thesis encompasses the entire RMB as a system. The previous authors[14-24] did not attempt to reach the stage of producing a practical design tool for practitioners; to achieve an optimal design of the entire RMB as a single harmonised system.

Animal behaviour requirements have largely been addressed by researchers dealing with RMBs (a broad survey is given by Ketelaar-de Lauwere[9]). The present thesis integrates cow behaviour into the engineering design process, a model embedded in software that can run on the farmer's desk during a consultation.

3. Model limitations

Proper use of a model

The result of this study is the methodology itself, the method, the algorithm, or the 'technique' that has been developed and implemented into a software application. The numbers, figures, and computer displays (throughout the entire thesis) explain the proposed methodology, its capability and its scope within a given practical situation. The methodology applies to RMB design in general. However, layout, herd size, equipment, climate, breeding, management philosophy and other factors all influence cows' behaviour. Therefore, the optimum solution (the model result), can be considered as an optimum only for the barn under study. There is no intention to define a specific layout which could be transferred elsewhere without parameter adjustment and without running the model again.

Animal friendly and comfortable design

The designs of the milking robot itself, the concentrate self-feeder, the yoke gates, and the cubicles should be comfortable to the animal. The present paper assumes that these items had been properly developed by commercial companies, and that their potential capacity is known: either supplied by the producer or measured directly. The parameters (such as service times and transition matrix) can (and should) be updated for each farm application, according to technology advances.

Disadvantages of computer simulation

Computer simulation over comes some of the disadvantages of the mathematical approach (Chapters 2 and 3), and it provides a quite realistic modelling of the layout problem. The structure of the barn, facilities, cow movements, and constraints can be represented in detail, by means of animation, graphics display and virtual reality. However, simulation has drawbacks for barn modelling, since it demands:

1. Skilled and therefore expensive manpower (although direct experimental testing of different layouts is usually more expensive, particularly if measurements go wrong...).
2. A new type of data collection regarding cows behaviour and use of facilities, which does not depend on a specific layout. We refer to Chapter 1 for more details about data acquisition.
3. Sophisticated statistical tools to study the stochastic process, and to validate the model for each farm type.

4. Close collaboration between dairy researchers and computer scientists, who are usually not located in the same laboratories, both for model design and for validation.
5. Heavy computations to obtain data analysis and visual simulation of many cows.
6. Solution of complex implementation problems concerning the parallelism of concurrent process in the same site (feeding, cow transitions between facilities, milk and manure accumulation, ammonia emission, etc.).
7. The main limitation of simulation lies in the fact that there is no mathematical proof of the optimality of a solution (which is why our methodology starts [queuing theory: Chapters 2] and ends [metamodel: Chapter 6] with analytical optimisation).

The environmental conditions of the acquired data

The task of a modeller is to produce a valid yet simplified abstraction of the barn of interest. Modelled and actual responses will not be comparable if they are obtained under differing scenarios or environmental conditions. Further difficulty comes from the need to simulate a future layout of an individual RMB - the layout does not yet exist, the cows which will occupy it do not yet exist, the conditions in the building are difficult to predict and so are farmer's routines, management practices, feeding arrangement, etc. The model assumptions are that the barn facilities, cows, etc. (the so called "system") are subjected to changes of state, relative to the conditions at a certain moment in time, which results from the initiation of complicated activities. This comprises a '*discrete event dynamic process*', which can be mathematically modelled. The advantage of the modularity approach (used in the present thesis) is that the modules can be independently tested (e.g., by mean of using a 'correlated inspection approach'). There is still no certainty that the interactions between the modules are correct but at least the sources (the facilities) of the interactions are correctly designated. The facility usage by the cows and the interrelations between the barn facilities in the present study were empirically measured (Chapter 1) and were argued over by the team working on the project, but if the specific layout that were chosen in Chapter 1 is misleading the animal behaviour measurements, then the model would not be valid.

However, in Chapter 1 we gave the cows unlimited facility allocation, and the freedom to choose. Therefore, the measurement circumstances suggest an ideal situation (from the cow's point of view) that can be extrapolated to more crowded situations without adversely affecting animal welfare. In other words, the model presents an optimal situation from the cow's point of view, and a deviation from a solution suggested by the model, aiming to reduce labour and building costs would be a compromise. If a very crowded situation were chosen, the designer should look also at the predicted available time windows. An available time window is a period of time during which a facility is idle; e.g., i) one of the proposed solutions in Chapter 6 results in 83% robot utilisation, i.e., for around 4 (out of 24 h) the robot is idle, no cow arrives; ii) also if an average two cow queue is chosen, (idle) time windows will be available, because the model is stochastic. *An available window* is the time for a cow of low hierarchical rank to 'sneak' into the robot.

In general, the herd social hierarchy can hardly affect a decision in an over-capacity situation; a low rank cow will synchronise her visiting times or will wait. In an overloaded situation, a low rank cow might be denied access, therefore, an additional design criterion should be 'enough available time windows' (together with queue length and utilisation) so that there is enough idle time for the lowest rank cow to make her visits. Thus, the model promotes the welfare of the low rank cows too. With today's milking parlours, low rank cows often leave the herd simply because they cannot express oestrus. A robot supports such cows, not only because of quantifying the available time windows, but also because it provides other measures for oestrus detection. Further research, designed to investigate the link between milk yield and the length of the robot's available time windows, will benefit the 'farmer's pocket'. Also, if there are not enough available time windows - the commercial version of the software application can give an alarm. Actually, defining enough eating time windows is almost equivalent to providing an adequate feed intake, assuming that if a cow has enough time in the forage lane she will use this time for eating. Obviously the eating time needed will depend on food composition, i.e., the quantity of long fibre in the ration, but further research into this question of 'needed eating time' may be of interest. Proper use of the model, taking into consideration the physiological needs for resting ('cubicle time') for all the cows in the herd, promotes this aspect of animal welfare also.

Cow traffic and cubicle housing

The model was found to be a valid representation of a real system (97.5% confidence level, Chapter 5). However, one should keep in mind that the same basic principles of cow traffic and cubicle housing were maintained in: the data source, the validation sites, and the farm in question. The present paper makes no claim for the validity of our optimal solution under completely different housing conditions or management principles (e.g., grazing or use of an open cowshed such as is found in Israel). Fortunately, the basic principles used in this study are in common use in today's RMBs. It is the responsibility of the modeller to ensure that the statistical distributions employed are the best for the intended barn.

Level of detail

Over-modelling (too much detail) increases the likelihood of errors and can extend the project duration; and sometimes additional detail may not lead to any better quantitative results. The perfect model would be the real system itself (by definition, any model is a simplification of reality). In practice, the model should be 'good enough' [25] or 'credible' [26] of which the criteria depends on the goals of the model[25,26]. Therefore, the aim should be for the BBS to hold those details absolutely necessary to support the decisions to be made. In the present study, different levels of detail were used in different section of the model. For example, it would not make sense to model activities associated with loading, moving and unloading the milk at the same level as the facilities or cows' activities. However, if a user were to run the software (after adjusting its parameters) and find out that the model was not valid under his specific real-life situation, he would be free to add more details into the simulation model until he finds it valid enough for his purposes. Among the additional details that could be programmed in is the herd's social hierarchy, which can be integrated by using priority-queue algorithms[27]. This modification would not be expected to influence the results for an average cow appreciably, but (if there were not enough available time windows) it might influence the queuing time of a very low rank heifer in a very crowded situation.

3. Unsettled exceptions and further research

The BBS software can simulate different robot positions in an RMB, but the exact optimal placement of the robot is not explicitly calculated in this version of the model. For example, if locations were chosen wrongly, there might be two robots installed in a single barn, with one of them is over-occupied and the second often idle. Robot locations are important but are limited by extraneous mechanical factors such as the distance to the milk container, accessibility of the milk tanker (a big truck, sometimes with a trailer), existing infrastructure, wind direction, sanitary regulations, drainage and canalisation. There are only a few acceptable positions in a farm, commonly at the edge or centre of the barn, and the options can be judged without simulation assistance.

Automatic drawing of the optimal solution is not embedded in the BBS software. When it was done in the past[28], there were several drawbacks: an automatic computer drawing might be schematic, and limited in variations, and might not be able to cope with all variations among existing facilities and specific farmer preferences[28]. Therefore, optimal positioning and automatic drawing of the layout are not performed by the BBS (although, technically speaking, this could be done easily: today, parametric drawing is an integral part of many off-the-shelf CAD/CAM software packages[29,30]). Also, positioning and automatic drawing were left out of the model in order to leave the designer certain degree of freedom for innovation, to develop creative thinking in designing shapes, and to include non-standard wishes of the farmer.

The RMB design is an iterative engineering process, which involves three different types of software: CAD drawing, the BBS, and economic evaluation. Integration of the three types together into a single integrated package would be more convenient, but might impair the freedom of a designer who likes to work with his/her preferred CAD or economic software applications.

Determination of the investment requirements for new facilities or herd expansions and estimation of the economic costs and benefits are not directly addressed by the BBS. However, facility utilisation is associated with 'cost per cow; and economic evaluations are already available from other software applications[31,32,33] for the use of consultants, and educators. It could be that integrating economic evaluation into the BBS model might influence its choice of optimal layout for a farm, in which case, such integration should be the subject of further research.

The chapter (5) on validation and, in particular, its problematic 10-cow scenarios show the importance of appropriate data from a reliable farm. More information should be accumulated in order to address a full range of practical situations. However, data will be accumulated anyway, in the course of working with the proposed design methodology on a daily basis. It is now up to the industry to implement the proposed design methodology. As an increasing number of RMBs are designed by the BBS, an established database will be accumulated. Each new RMB design will contribute to and enlarge the collective database and thus the data validation of the next farm to be designed. The RMB designs, layouts and operational data should be stored in the public domain (such as an Internet site) accessible to anyone, in accordance with the principal of free dissemination of scientific knowledge. It is the responsibility of the modeller to ensure that the statistical distributions employed in each case are the best for his intended barn.

4. Possible practical implementations

In the 1980s and 1990s, modelling, systems engineering, OR and computer simulation have revolutionised the design process of complex systems such as manufacturing systems, logistics, communication networks, banks, supermarkets and resource allocation[34]. Likewise, the present study may be said to be a contribution to a further revolution, this time in the design of livestock systems. In planning a new barn or redesigning an existing one, RMB simulation is a tool to help barn designers make the right decision. The simulation model can provide quantitative measures of system performance as well as graphical animation that gives insight into the workings of a complex dynamic barn. Using the RMB simulation, a model of a future barn can be created, which will help to make effective decisions. It will provide information such as, the number of cows waiting for food in a new forage lane, the utilisation rate of a new milking robot and the number of milkings per day to be gained by implementing a new facility configuration or a new feeding routine. In general, it is possible to predict how the system will respond to changes in design or operation before the barn is built, and to compare what will happen under a variety of scenarios.

There are numerous potential applications, of which only a few are listed below. Using simulation, "what-if" questions such as the following can be answered:

- ☐ "What if we buy a milking robot instead of using the old milking parlour?". Should there be 2,3 or 4 stalls ?
- ☐ "What if the milk quota were to be increased by 25, 50, 100%?". Should we build more cubicles, with the objective of accommodating more cows in the same barn?.
- ☐ "What if we build a concentrate-feeder in this particular location?" , will it support the planned cow traffic?

Using the entire methodology (including the optimisation modules, analytical models, and aspiration levels for animal welfare) enables the following:

- calculation of optimal facility allocation: the numbers of cubicles, forage lane positions, water troughs, concentrate feeders, and robots needed
- advising to the individual farmer in the choice of robot location and cow traffic routine, i.e., free, semi-forced or forced cow traffic (there is an enormous variation in opinions and practices, and a scientifically based analysis should be convincing even in the face of possible prejudices of the traditional farmer);
- calculation of the required floor space in front of each facility (a waiting area);
- prediction of the influence of a new feeding routine (for example, buying a mixer wagon, which would prepare TMR for one or two feedings per day, on the number of cow visits to the robots);
- advice to the individual farmer as to whether there is need for a separation area, and what should be its size and location;
- advice to the individual farmer as to the duration and frequency of automatic cleanings (in Holland, the minimum is three per day, but in hot climate or for the cheese industry a farmer might need more);
- benefit analysis of a selection unit in a specific problematic situation, taking into consideration the influence of such units on cow behaviour and cow traffic;
- pointing out a necessary technical improvement and its effect on the entire system performance. For example, the importance of milk flow rate might direct national breeding policy;
- advice before installation as well as improving the use of the robot after installation, for example, when cow visits to the robots are not frequent enough - how to change feeding and cleaning farm routines;
- analysis of an interesting real-life farm for use as a case study. For example, one farm in the north of the Netherlands, milks 70 cows with one robot and accomplishes more than 230 milkings per day!, while another produces 750,000 litres per year with only one robot. There may be applicable knowledge to be gained from modelling and analysing individual "extreme cases";
- embedding the design methodology in a user-friendly interface to run on a laptop computer, so that it is ready for use by a consultant/ adviser/ salesman at the farmer's dining-table, who can then input all the farmer's preferred variables, and
- the farmer can gain the assurance before building that the proposed design would actually meet his specified requirements.
- the robotics industry can collect data in the course of day-to-day designing. The RMB designs, layouts and operational and management data should be stored in the public domain such as

an Internet site. The site manager will probably assist in modelling and selecting a suitable data source, but it is the responsibility of the modeller to ensure that the statistical distributions employed are the most appropriate for the intended barn.

- The animal-welfare aspiration model (used for defining 'cow-friendly' values of queue length and facility utilisation) has opened a way for designing barns based on animal welfare requirements. An optimal design should balance two conflicting requirements: on the one hand, the economic need for high facility utilisation and on the other hand, animal welfare. Such a design may help to stimulate the development of an animal welfare "ISO" certification, which would enable authorities to gain assurance ahead of its implementation that a proposed design would meet pre-specified animal welfare requirements.
- More theoretical advantage may arise from the operational research into facility usage under very loose housing, which has opened the way for the use of systems theory and mathematical models in the design of robotic milking barns.

5. Conclusions

Milking robots should be integrated into dairy barns, but the barn in the traditional farm is designed around the milking parlour. Thus, barns must be redesigned for robotic milking. In order to solve this problem, a behaviour-based simulation model was developed and validated. This study has achieved:

- prediction of utilisation of the facilities, including the robots, the cubicles, the forage lane, the concentrate feeders and the water troughs;
- prediction of cow queue length, of the number of cows waiting for an unavailable facility and of the average waiting time;
- calculation of the optimal facility allocation and design of the barn layout;
- prediction of the effects of particular robot operations, management practices, and cow traffic on the performance of the entire RMB system.

The model can take into consideration:

☐ the effect of cow behaviour on facility design and usage;
☐ existing facilities, barn design and layout;
☐ farmer preferences, feeding routine and management practices;

The core idea is that systems engineering and operational research techniques can play an important role in the design of livestock systems. The features listed above were achieved by:

- quantifying cow behaviour and facility usage;
- developing an queuing-network model of the entire robotic barn;
- developing an aspiration-level model that integrates animal welfare into the design process;
- developing a behaviour-based computer simulation;

- validating the model under a variety of scenarios and adjusting sensitive parameters to suit the individual farm;
- applying metamodel and linear-programming techniques in order to achieve the global optimum.

In general, this research has progressed to a point at which the behaviour-based simulation is adjustable for any farmer or site, with no necessity for additional data collection under research conditions. However, more data from more farms may improve the model's validity, and such data can be collected by the industry while designing barns on a daily basis. The onus is now on the industry to implement the proposed design methodology[35].

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Summary

1. Objective and scope

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

The traditional barn has a milking parlour 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, 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 a system layout; an optimal layout balances adequate facility capacity against over capacity. It should balance animal welfare, on the one hand, and facility utilisation, on the other hand. So, the two conflicting requirements (to be optimised) are the economical need for high facility utilisation, 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 behaviour). There is also a 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 behaviour 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 should be 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 finding 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.

The study was intended to contribute in three ways. 1) To develop a science-based design methodology for the RMB, taking into account the many factors that directly influence the design, such as 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 barn 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 generalised to other cases.

2. Operational research into facility utilisation

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 utilisation in a robotic milking barn - independently of the barn layout. To minimise 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 fed continuously round the clock. The activities of each cow in the group were monitored on an individual basis. The intensity and sequence of use of the facilities and cow behaviour were studied and statistically quantified. 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 by the evening was pushed toward the cows. The main finding of operational research 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.
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 utilisation.

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 behaviour, and influenced the entire system performance.
e) In our experiments, the observed cubicle utilisation never exceeded 75%, which suggests that it would be feasible to have fewer cubicles than cows without adversely affecting cow behaviour.
f) Robot utilisation 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.

The operational research into facility utilisation forms the central theme of this thesis: quantifying animal behaviour in relation to facility utilisation 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.

3. Developing the queuing network model

A closed queuing network (CQN) model for a robotic milking barn was developed. We use an approximate mean-value algorithm to evaluate important performance criteria such as the number of waiting cows, their waiting time and the utilisation 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. It enabled the designer to judge whether the layout meets the cows' needs for facilities allocation.

The main conclusions were that the CQN model 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 utilisation 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. Unfortunately, queuing networks are still uncommon in the analysis and design of livestock housing. As the thesis has demonstrated, these techniques appear to form a useful tool for solving RMB design problems.

4. Computer simulation and model validation

A behaviour-based simulation (BBS) model, which enables a designer to optimise facility allocation in a barn, has been developed and validated. 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 experiments: (i) observation of cow behaviour in real (non-simulated) barns, and (ii) computer simulation. The measurements from three real robotic barns were compared with simulation data under a variety of scenarios, including commercial barns. 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. This hypothesis was tested statistically and was not rejected at $\alpha=2.5\%$.

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 the 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.

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 (a simulation run took only 1½ minutes on a 200 MHz PC).

Having been validated, the simulation model becomes a practical design tool for optimising a barn layout.

5. Metamodel and optimisation

The BBS model was integrated with regression metamodel, full factorial design, and optimisation algorithms. 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.

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.

6. Practical implementation and conclusions

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 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:

- to predict facility utilisation and cow queue length,
- to calculate the optimal facility allocation: the necessary numbers of cubicles, forage lane positions, water troughs, concentrate feeders and robots;
- 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
- 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 that there is no necessity for further data acquisition under research conditions. However, more information should be accumulated in order to address the full range of practical situations, and additional data from more farms may also improve the model validity. The onus is now on the industry to implement this proposed design methodology on a daily basis. Data should be collected by the industry in the course of day-to-day designing, and the RMB designs, layouts and operational data should be stored in the public domain (such as an Internet site) accessible to anyone, in accordance with the principles of free dissemination of science.

Samenvatting

1. Doel en toepassingsgebied

Huidige ontwikkelingen leiden tot een afname van het aantal rundveebedrijven, het toenemen van de omvang van de resterende bedrijven en voortgaande modernisering, veelal door het installeren van een robot melksysteem (RMS). De melkrobot heeft invloed op arbeid, productiviteit van de koe, dierenwelzijn, voerstrategieën, stalontwerp en management. Al deze apecten moeten worden beschouwd bij het ontwerpen van een stal met een RMS.

Het ontwerp van de traditionele stal is gericht op de melkstal, waardoor de introductie van een melkrobot kan leiden tot het moeten herzien van het stalontwerp. De werkelijke capaciteit (prestatie) van de melkrobot is mede afhankelijk van het gemak waarmee de koe de robot kan bereiken. Het totale systeem (stalontwerp, routines voor voerverstrekking en koeverkeer, management) moeten het 'vrijwillig melken' bevorderen, dat wil zeggen: zij moeten een voldoende hoge frequentie van bezoeken van de koe aan de melkrobot verzekeren. De capaciteit van voorzieningen en ruimten binnen de stal zijn bepalend voor de vormgeving van het systeem. Om tot een optimaal ontwerp te komen, wordt de situatie waarin sprake is van onvoldoende capaciteit van de voorzieningen afgewogen tegen het bestaan van overcapaciteit. De tegengesteld werkende krachten die in de optimalisatie een rol spelen, zijn de uit bedrijfseconomisch oogpunt nagestreefde hoge bezetting van voorzieningen enerzijds en de wens het, uit oogpunt van dierenwelzijn, altijd beschikbaar willen hebben van voorzieningen anderzijds. Het resultaat moet worden geïmplementeerd in de managementstrategieën en het fysieke ontwerp. Een complicatie in het optimalisatieproces is het feit dat de capaciteit van iedere voorziening in een stal met RMS (bv. melkrobot, voerhek, krachtvoerstation) afhankelijk is van de bereikbaarheid voor de koe. Tevens is er sprake van een grote variatie in de mate waarin veehouders hun melkveebedrijf organiseren en in plaatselijke omstandigheden. Het optimale stalontwerp kan dan ook van geval tot geval verschillend zijn. Omdat de melkrobot een relatief nieuw product is, is relatief weinig ervaring opgedaan met het ontwerpen van stallen met een RMS. Er is dan ook behoefte aan een ontwerpmethode voor rundveestallen met een RMS waaraan wetenschappelijke uitgangspunten in tegenstelling tot subjectieve ervaringskennis ten grondslag liggen. Diergedrag en dierenwelzijn, interactie tussen koeien, aantal en capaciteit van de voorzieningen, managementstrategieën en veehouder- en situatie-afhankelijk instelbare invoerparameters moeten in de ontwerpmethode worden meegenomen. Het ontwerp van een stal met RMS is dan ook een multidisciplinair onderzoeksgebied dat vraagt om een interdisciplinaire benadering.

De nieuw ontwikkelde methode moet worden geïmplementeerd in ontwerpmiddelen (bv. een computerprogramma) waarvan zowel het onderzoek als de praktijk gebruik kunnen maken. Hierbij kan worden gedacht aan toepassing door wetenschappers, ontwerpers, adviseurs en fabrikanten van producten. Het doel van dit onderzoek was het ontwikkelen van een methode waarmee het optimale ontwerp van een rundveestal met RMS kan worden vastgesteld voordat de uitvoering plaatsvindt. Het resultaat, het optimale ontwerp bij een RMS, moet kunnen worden afgestemd op condities die specifiek geldig zijn voor een bepaald melkveebedrijf. De ontwerpmethode moet algemeen toepasbaar zijn.

Dit onderzoek moest op drie gebieden bijdragen leveren. 1) Het ontwikkelen van een methodiek met wetenschappelijke basis voor het ontwerpen van een rundveestal met een RMS, rekening houdend met vele factoren die invloed hebben op het ontwerp (bv. capaciteit en gebruik van voorzieningen, diergedrag, voer- en managementstrategieën). 2) Het omzetten van de methodiek in een praktisch hulpmiddel, ingebouwd in een gebruikersvriendelijk computerprogramma, gereed voor gebruik in de praktijk tijdens een ontwerpsessie. 3) Het uitwerken van voorbeelden die de ontwikkelde methodiek illustreren, de complexiteit van het vinden van een optimale oplossing toelichten en die inzicht geven hoe oplossingen onder andere omstandigheden toegepast kunnen worden.

2. Operationeel onderzoek naar de benutting van voorzieningen

Vier experimenten zijn uitgevoerd, twee onder onderzoeksomstandigheden en twee bij commerciële melkveebedrijven. In totaal 200 koeien waren bij deze experimenten betrokken. In het eerste experiment kregen de koeien volledige vrijheid van keuze. Aangenomen werd dat de activiteiten van de dieren daarom zodanig waren, dat de negatieve invloeden op het eigen welzijn zo gering mogelijk waren. Het doel van dit experiment was het verkrijgen van informatie over de stochastische achtergronden van het gebruik van voorzieningen in een rundveestal met RMS, zo onafhankelijk mogelijk van het stalontwerp. Om de eventuele beperkingen te minimaliseren die de koeien desondanks toch ondervonden bij het verkrijgen van toegang tot de voorzieningen, werd minder dan de helft van het aantal koeien waarvoor de stal was ontworpen, gehuisvest. Voer was 24 uur per dag beschikbaar. De activiteiten van iedere koe werden vastgelegd, bestudeerd en statistisch gekwantificeerd, evenals de intensiteit en volgorde van het gebruik van voorzieningen. Tijdens het tweede experiment werd tweemaal per dag ruwvoer verstrekt. Het aantal koeien was gelijk aan de capaciteit van de stal. Het doel van dit experiment was het valideren van het ontwikkelde model onder andere omstandigheden dan degene die van toepassing waren toen het model werd ontwikkeld (ander stalontwerp, voerstrategie en aantal dieren). Groepen van respectievelijk 10, 20 en 30 koeien werden gehouden in een ligboxenstal geschikt voor het huisvesten van maximaal 30 koeien. Iedere groep werd gedurende 3-4 weken (excl. de opstartperioden) geobserveerd. Het derde en vierde experiment werden uitgevoerd op twee commerciële bedrijven, representatief voor de bedrijven in Nederland. Het doel was het valideren van het model onder omstandigheden zoals gebruikelijk in de commerciële veehouderij en bij toepassing van een ander type robot. Op het eerste, reeds bestaande, bedrijf werd een RMS, na het doorvoeren van enkele stalaanpassingen, geïnstalleerd. Bij het tweede bedrijf was sprake van een volledig nieuwe stal, ontworpen voor melken met een melkrobot zodanig dat eigenlijk meer dan één RMS moest worden toegepast. Tijdens de 4-5 weken durende experimenten werden op de bedrijven 60 koeien gemolken met één melkrobot. Het ruwvoer werd 's ochtends met een voerwagen verstrekt. 's Avonds werd het in de voergang resterende voer naar de koeien geschoven. De belangrijkste resultaten van het onderzoek in de stallen met RMS zijn:

g) de tijdstippen waarop de voorzieningen worden bezocht (aankomsttijd) en de lengte van de bezoeken (verblijftijd) aan de voorzieningen in een stal met een RMS kunnen worden beschreven met exponentiële, normale, Weibull, log-normale en bèta verdelingen;

h) de stal met een melkrobot is in feite een gesloten wachtrij netwerk: een aantal voorzieningen (melkrobots, krachtvoerstations, voerhek, ligboxen, drinkbakken, etc.) waar de koeien moeten worden ontvangen, is beschikbaar. Na het bezoek aan voorziening i gaat een koe verder naar voorziening j, weergegeven in een matrix met kansen voor alle verplaatsingen die tussen voorzieningen mogelijk zijn ('verplaatsingen matrix');

i) de verplaatsingen matrix geeft aan dat na 90% van de bezoeken aan de melkrobot het krachtvoerstation wordt bezocht. Het krachtvoerstation (losstaand of in de melkrobot geplaatst) is dus een effectieve voorziening om de koeien een zekere mate van gedwongen koeverkeer op te leggen. De verplaatsingen matrix geeft ook aan dat vele bewegingen tussen het voerhek en de ligboxen en tussen het voerhek en de drinkbakken plaatsvinden. Als deze bewegingen door het hanteren van gedwongen koeverkeer niet kunnen plaatsvinden, kan dat negatieve gevolgen hebben voor het dierenwelzijn en voor de voeropname;

j) twee pieken tijdens de opname van ruwvoer domineren het voergedrag van de koeien in de tijd en beïnvloeden de prestaties van het gehele systeem;

k) de tijdens de experimenten waargenomen bezettingsgraad van de ligboxen was nooit hoger dan 75%. Dit geeft aan dat het mogelijk is het aantal ligboxen lager te kiezen dan het aantal te huisvesten koeien, zonder dat dit van invloed is op het koegedrag;

l) de bezettingsgraad van de melkrobots op de twee commerciële bedrijven met een RMS was relatief hoog (ca. 85% op dagbasis). De prestaties betreffende het aansluiten van de melkrobot kwamen overeen met de prestaties die in de praktijk vereist zijn (1,25% van de bezoeken leidde niet tot het aansluiten van de melkrobot, hetgeen 1,00% van de beschikbare tijd van de melkrobot vergde). Dit doet vermoeden dat melken met een melkrobot zich heeft ontwikkeld tot een techniek die voldoende betrouwbaar is om op grote schaal te worden toegepast.

Het onderzoek naar de benutting van voorzieningen brengt het centrale thema van dit proefschrift naar voren: het kwantificeren van de relaties tussen diergedrag en benutting van voorzieningen als een in de tijd continu stochastisch proces maakt het mogelijk om systeemontwerp en theorieën (zoals wachtrij netwerk modellen. Markov ketens en computersimulatie) toepasbaar te maken bij het ontwerpen van stallen met een RMS.

3. Het ontwikkelen van een wachtrij netwerk model

Een gesloten wachtrij netwerk (closed queing network, CQN) model voor een stal met RMS is ontwikkeld. Een benaderingsmethode wordt gebruikt voor het berekenen van de gemiddelden van belangrijke prestaties zoals het aantal koeien in een wachtrij, de wachttijd en de benutting van voorzieningen in de stal. De wijze waarop resultaten worden weergegeven sluit aan op de bij de veehouder levende gedachten (dierenwelzijn weergeven via de lengte van wachtrijen en wachttijden; kosten via de bezettingsgraad van voorzieningen). De prestaties van de stal worden ook visueel weergegeven zodat de ontwerper kan beoordelen of het ruimtelijk ontwerp met de voorzieningen aansluit op de behoeften van de koeien.

De belangrijkste conclusies zijn dat geen exacte oplossing voor het CQN model kan worden gevonden, maar dat het beschrijven van de tijdstippen van aankomst en het berekenen van gemiddelden een goede benadering van de werkelijkheid geven (nauwkeurigheid van 99.5-99.9% voor het gebruik van voorzieningen; 98-99% voor de gemiddelde wachttijd). Door het verwachtingspatroon te gebruiken bij het beoordelen van een ontwerp kan een stal met RMS voldoen aan zowel economische als dierenwelzijn eisen. De resultaten geven ook aan in welke richting kan worden gedacht bij het vastleggen van dierenwelzijn in normen, bijvoorbeeld ISO. Helaas is het nog niet gebruikelijk netwerken bij het analyseren en ontwerpen van gebouwen voor de dierhouderij te gebruiken. Zoals getoond kunnen deze technieken echter een bruikbaar instrument zijn bij ontwerpvraagstukken waarin een RMS een rol speelt.

4. Computersimulatie en modelvalidatie

Een op diergedrag gebaseerd simulatiemodel is ontwikkeld en gevalideerd. Dit model maakt het voor de ontwerper mogelijk om de optimale capaciteit van voorzieningen in een stal te berekenen. Het model vraagt minder vereenvoudigende aannames dan het wachtrij netwerk model. Simulaties maken het mogelijk uitrusting, ruimtelijk ontwerp en managementstrategieën gezamenlijk te evalueren. Twee typen onderzoek zijn uitgevoerd: i) observatie van koegedrag in een werkelijke, niet gesimuleerde situatie, en ii) computersimulaties. De resultaten verkregen op drie bedrijven met een stal met een melkrobot werden vergeleken met de resultaten van simulaties met een verscheidenheid aan scenario's, inclusief commerciële bedrijven. De belangrijkste conclusies volgend uit de ontwikkeling van het simulatiemodel, de simulaties en de experimenten zijn:

a) het simulatiemodel is een betrouwbare en nauwkeurige weergave van het werkelijke systeem. Deze hypothese is statistisch getoetst en niet verworpen bij $\alpha = 2,5\%$;

b) het simulatiemodel en de bijbehorende animatie verbeteren de communicatie tussen de gebruiker, c.q. veehouder, en de ontwerper. Het schept de mogelijkheid door de veehouder ingestelde factoren in het model te integreren en geeft ontwerpvarianten voordat de uitvoering van het bouwwerk start. De veehouder kan nog voor de uitvoering de verzekering krijgen dat het voorgestelde ontwerp voldoet aan zijn eisen. Het vertrouwen in het model wordt nog versterkt doordat het een waarheidsgetrouwe weergave van de stal geeft;

c) een eerste ontwerp kan worden aangepast om tot een uitgebalanceerd systeem te komen, een zogenaamd lokaal optimum. Dit kan plaatsvinden binnen een relatief kort tijdsbestek (op een 200 MHz PC duurt een simulatie ongeveer 1,5 minuut).

Na validatie is het simulatiemodel een praktisch toepasbaar hulpmiddel bij het optimaliseren van het stalontwerp gebleken.

5. Metamodel en optimalisatie

Het op diergedrag gebaseerde simulatiemodel is geïntegreerd met een regressie metamodel, een zoekroutine waarin alle mogelijke combinaties worden meegenomen ('full factorial design') en algoritmen voor optimalisatie. De transformatie bleek te leiden tot een eerste orde polynoom zodat Kuhn-Tucker condities zowel noodzakelijk waren als volstonden voor het vinden van een globaal optimum. Gangbare algoritmen als projectiemethoden of de Simplex methode waren toepasbaar. Omdat de integratie het mogelijk maakte een globaal optimum te vinden, completeerde het de mathematische ontwikkeling van de geïntegreerde ontwerpmethode.

Onder voor twee specifieke stallen A (71 koeien) en B (132 koeien) geldende omstandigheden was de optimale capaciteit van voorzieningen, respectievelijk, 36 plaatsen aan het voerhek en 60 ligboxen (stal A; 1 melkrobot) en 103 plaatsen aan het voerhek en 105 ligboxen (stal B; 2 melkrobots). Het optimale ontwerp berekend in de case study is uniek voor een bepaalde veehouder, maar de ontwikkelde methodiek is universeel toepasbaar omdat de instelwaarden van parameters kunnen worden aangepast aan de wensen van de veehouder, de lokatie en het type melkrobot.

6. Implementatie in de praktijk en conclusies

Modelleren, systeemontwerp, operationeel onderzoek en computersimulatie hebben geleid tot revoluties op het gebied van het ontwerpen van complexe industriële systemen. De in dit proefschrift beschreven studie heeft de potentie in zich bij te dragen aan een verdere revolutie, dit keer met betrekking tot het ontwerp van dierhouderijsystemen. Met de beschreven ontwerpmethodiek kan een te realiseren stal worden ontworpen. Omdat de prestaties van de stal kunnen worden voorspeld voordat met de uitvoering wordt begonnen, kunnen scenario's worden doorgerekend (bv. invloed van veranderingen in het ontwerp of de managementstrategie) en kunnen beslissingen worden genomen. Het is onder andere mogelijk om:

- de benutting van voorzieningen en de lengte van wachtrijen te voorspellen;
- de optimale capaciteit van voorzieningen te berekenen (aantal ligboxen, vreetplaatsen aan het voerhek, waterbakken, krachtvoerstations en melkrobots);
- de veehouder te adviseren bij het kiezen van de lokatie van de melkrobot, bij het realiseren van het gewenste koeverkeer, bij het kiezen van de vereiste vloeroppervlakte (wachtruimten), voerstrategie, afzonderingsruimten, automatische reiniging;
- voor de uitvoering de zekerheid te verkrijgen dat het voorgestelde ontwerp voldoet aan gespecificeerde eisen.

In het algemeen gesproken heeft het in dit proefschrift beschreven onderzoek het punt bereikt waarop simulaties op basis van diergedrag voor iedere veehouder of lokatie kunnen worden uitgevoerd, zodat geen behoefte bestaat aan het onder onderzoekscondities verkrijgen van nadere informatie. Additionele informatie moet echter worden verzameld om het gehele scala van praktische situaties te kunnen omvatten en om de deugdelijkheid van het model te verbeteren. Het bedrijfsleven staat nu voor de uitdaging de voorgestelde ontwerpmethodiek in de dagelijkse praktijk te gebruiken. Gegevens verzameld door het bedrijfsleven tijdens de ontwerpsessies, de ontwerpen van stallen met een RMS, plattegronden en operationele gegevens zouden moeten worden opgeslagen op een publieke plaats (bv. een internetpagina), vrij toegankelijk voor iedereen volgens het principe van vrije verspreiding van kennis.

CURRICULUM VITAE

Ilan Halachmi was born in 1965 in Moshav Kefar-Yehoshua, in Israel. He studied in and graduated from the local high school, and then served four years in the Israel Defence Force (military rank: captain). Afterwards, he worked on the family farm while studying for engineering degree in the Technion - Israel Institute of Technology, Haifa (B.Sc. 1994). During 1995-1996 he acquired his degree in Industrial Engineering and Management (Ben-Gurion Univ., M.Sc., 1996), while working as a research engineer in the institute of Agricultural Engineering, A.R.O., the Volcani Centre. In 1997 he went to the Netherlands to work in IMAG-DLO for his Ph.D. from Wageningen Univ. Most recent field of research: (1) Design and implementation of automatic, mobile drinking machine for calves; (2) Modelling the individual voluntarily feed intake of the dairy cow; (3) Design and implementation of a control system for the individual feed intake of a dairy cow, kept in a group. Each project involved mechanical design, building a prototype, algorithm and software development, system engineering and operational concept under Israeli conditions. (4) Since 1997 he has been working on optimising robotic milking barns.

Married to Shuli Halachmi, one daughter: Algom.

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תקציר

5. מודל-על ואופטימיזציה (Metamodel and optimisation)

סימולציית המחשב הורחבה בעזרת במודלים הבאים: רגרסיה regression metamodel תכנון פרמטרי (full factorial design) ואלגוריתם לאופטימיזציה. הטרנספורמציות הניבו פולינום מדרגה ראשונה לכן תנאי קון-טאקר (Kuhn-Tucker) הכרחים ומספיקים למציאת נקודת האופטימום (גלובלי). בעזרת שיטות מקובלות (Projection methods or Simplex) ניתן למצוא את נקודת האופטימום ובכך הושלם החלק המתמטי של המודל.

בתנאים הקיימים בשני המשקים המסחריים שפורטו בעבודה, המודל מצא את ההקצאות (facility allocation) האופטימליות הבאות: משק A: רובוט אחד, 36 עמדות בפס האבסה, 60 תאי-רביצה, מספיקים ל- 71 פרות. משק B: שני רובוטים, 103 מקומות בפס האבסה, 105 תאי-רביצה, מספיקים ל- 132 פרות. הפתרון האופטימלי הנ"ל הוא ייחודי לרפתות מסוימות שעבורם הורץ המודל. אבל השיטה קבילה בכל מקום, בכל רפת ניתן להריץ את המודל ולחשב את הפתרון האופטימלי המסוים לאותה רפת - בהתאם לתנאים המקומיים, סככות קיימות, ניהול, האבסה, סוג הרובוט, ממשק וכ"ו הקיימים ברפת המסוימת.

6. יישום ומסקנות

בעבר, מודלים מתמטים, הנדסת מערכת (systems engineering) , חקר ביצועים (operational research), וסימולציית מחשב חוללו "מהפכה" בתכנון רצפות יצור, רשתות תקשורת, בנקים, סופרמרקטים במילים אחרות - מערכות דינמיות מורכבות. אולי אנו בפתחה של מהפכה נוספת, הפעם תכנון רפתות רובוטיות בעזרת אותם כלים. כפי שהודגם בתזה זו, שימוש בכלים אלו מאפשר לחזות את התנהגות הפרות וביצועי כלל הרפת לפני שבונים אפילו גדר אחת..., ניתן להעריך את התוצאה שתיגרם בגלל שינוי במבנה (design) או בהפעלה (operation). ולהשוות פוטנציאל יצור במגוון תרחישים. בין היתר, אפשר:

- לחזות נצילות כל מתקן (רובוט, מאביס, פס האבסה וכ"ו) ברפת
- לחשב את התכנון האופטימלי: מספר רובוטים, מספר מאביסים, אורך פס האבסה, מס תאי-רביצה מס שקתות מים וכ"ו
- לייעץ לרפתן המתלבט במיקום רובוט, תנועת הפרות (*cow traffic routine*), גודל חצרות, גודל חצר המתנה, חצר טיפולים, הפרדה אוטומטית, שגרת חלוקת מזון, ניקוי.
- להיות בטוח, לפני התקנה, שהתכנון המוצע עומד בקריטריונים שהציב הרפתן

באופן כללי, מחקר זה הראה שסימולציית מחשב המבוססת על התנהגות הפרות ניתנת להתאמה אישית לכל רפתן ולכל אתר. אינפורמציה נוספת ממספר גדול של משקים תשפר את אמינות המודל ותאפשר לפתור מגוון נוסף של בעיות בביטחון רב יותר. נתונים נוספים יאספו תוך-כדי עבודה יום-יומית עם המודל לכן אין צורך באיסוף נתונים נוסף בתנאי מחקר מבוקרים. הנתונים שיאספו על ידי התעשייה מתכנון רפתות, נתוני ניהול ונתוני הפעלה צריכים להיות ברשות הציבור, למשל באתר אינטרנט זמין לכל. עכשיו, האצבע מופנית לתעשייה שצריכה לאמץ את שיטת התכנון החדשה ככלי עבודה יום-יומי.

1.25% מהמקרים שגזלו 1.00% מזמן הרובוט). לכן, ניתן להסיק שרובוט חליבה עבר את רוב מחלות הילדות, קרי, הגיע לרמת ביצועים ואמינות מספקת למעבר משלבי פיתוח לייצור המוני.

חקר הביצועים של רפתות רובוטיות העלה את הרעיון הבסיסי של עבודת מחקר זו: כימות ומידול התנהגות הפרות במונחים של תהליך סטוכסטי רציף (a continuous-time stochastic process) פותח את הדרך לשימוש בתאוריות מתחום הנדסת מערכות (systems engineering) וכלים מתמטים השאולים מרשתות תקשורת ותורת התורים (queuing network), שרשרות מרקוב (Markov chain) וסימולצית מחשב, לתכנון הרפת.

3. פיתוח מודל רשת תורים (Queuing network model)

פותח מודל רשת תורים הניתן לפתרון על ידי שימוש בטכניקת "אנליזת ערך ממוצע" (mean value analysis) . המודל מחשב קריטריונים לתכנון כגון מספר פרות ממתינות בתור, זמן המתנה, ונצילות של כל מתקן ומתקן ברפת. המודל לוקח בחשבון את רמת השאיפות של הרפתן (למשל אורך תור שהוא מגדיר לפרותיו), עלויות ומספק ניתוח חזותי (visual analysis) של ביצועי הרפת.

המודל רשת תורים אינו יכול להיפתר באופן אנליטי אבל בצורה איטרטיבית ניתן להתכנס לפתרון של נצילות מתקני הרפת בדיוק של 99.5-99.9% ופתרון אורך התור בדיוק של 98-99%. שילוב דרישות תכנון המוגדרות על ידי הרפתן כחלק מהמודל מאפשר עמידה באילוצים כלכלים תוך שמירה על רווחת בעל-החיים (animal welfare). בנוסף, המודל ופתרונו מציעים גישה להגדרת תקן ISO לרווחת בעל-החיים.

כיום, תכנון הרפת בהתאם לכלי תורת התורים (שפותחה לרשתות תקשורת) עדיין לא נפוץ. כפי שהודגם בעבודה זו, כלים אלו יכולים להיות מועילים לפתרון בעיות תכנון רפת רובוטית הצצות מידי יום.

4. סימולציית מחשב ואימות המודל (Computer simulation and model validation)

פותח מודל סימולציה המבוסס על התנהגות הפרות שמאפשר לתכנן את הרפת האופטימלית בהתאם לדרישות האישיות של הרפתן והתנאים המקומיים ברפת. המודל נוסה ודיוקו אומת בתנאי רפתות מסחריות בהולנד. מודל הסימולציה דורש פחות הנחות והפשטות הנדרשת למודל רשת תורים. ניסוי סימולציה מאפשר להעריך את השתלבות מערך המבנה, המכונות, המתקנים התנהגות הפרות, שיטת ניהול ושגרת האבסה כמערכת אחת הפועלת בהרמוניה.

על מנת לאמת את המודל ביצענו שני סוגי ניסוים (1) תצפיות ברפת אמיתית (לא סימולצית מחשב), (2) סימולצית מחשב. מדידות משלוש רפתות אמיתיות הושוו למודלים של סימולציה במגוון תרחישים (scenarios). המסקנות העיקריות מאימות המודל היו, (1) אכן המודל אמין, מייצג את המציאות ברפת מסחרית ברמה סטטיסטית של $\alpha=2.5\%$. (2) מודל הסימולציה (הכולל אנימציה) משפר את התקשורת בין הרפתן למתכנן ובעצם מאפשר לרפתן לשלב למודל את כל הפרמטרים שמעניינים אותו, ושמשפיעים על התכנון. המודל מעלה אפשרויות תכנון שלא חשבו עליהן לפני הרצת הסימולציה ובכך תורם ליצירתית המתכנן. החקלאי מקבל ביטחון שהתכנון המוצע על ידי המהנדס אכן מקיים את דרישותיו ועובד בפועל. (3) תכנון ראשוני יכול להיות מהוקצע באופן איטרטיבי עד קבלת מערכת מאוזנת ואפילו אופטימלית (fine tuning and local optimum). לאחר האימות בתנאים מסחריים המודל הופך להיות כלי תכנון רפת רובוטית אופטימלית.

פתרונות למקרים כללים שניתן ליישמם גם במשקים שונים.

2. חקר ביצועים

בוצעו ארבעה ניסויים, שניים בתנאי מחקר ושנים ברפתות מסחריות. בניסוי הראשון ניתן לפרות חופש מוחלט לבחור את פעילותם ברפת (ללא מגבלות) מתוך הנחה שהפרות יבחרו את הפעילות המגבירה את רווחתן (Animal welfare). המטרה של ניסוי זה הייתה לבחון ולמדל את האופי הסטוכסטי של התנהגות פרות ברפת רובוטית, ללא תלות במבנה הרפת. כדי להקטין למינימום מגבלת הנגישות למתקנים, הרפת הכילה פחות מחצי מספר הפרות שלהן תוכננה, הנגישות לכל המתקנים הייתה מרבית, בליל הואבס בצורה רציפה סביב לשעון. פעילות כל פרה נמדדה ונרשמה על בסיס אינדוודואלי וסדר השימוש במתקנים, העומס בהם, והתנהגות הפרות נלמדו בצורה סטטיסטית. בניסוי השני בליל הוגש פעמים ביום ומספר הפרות הועלה למקסימום האפשרי ברפת. מטרת הניסוי הייתה לאמת את תקפות המודל בתנאים השונים מהתנאים שלפיהם פותח המודל (בעיקר מערך מבנים שונה, שגרת האבסה שונה ומספר פרות שונה). הנסויים השלישי והרביעי בשתי רפתות מסחריות במטרה לאמת את המודל בתנאים מסחריים ועם רובוט מסוג שונה. ברפת הראשונה הרובוט הותקן ברפת קיימת, ברפת השניה הרובוט הותקן ברפת חדשה שנבנתה במיוחד עבור רובוט וכל משק מנה כ- 60 חולבות. בליל חולק בבוקר על - ידי עגלה מערבלת שוקלת והשאריות קורבו לפרות אחרי הצהרים.

המסקנות העיקריות מחקר הביצועים ברפת רובוטית:

I) גישת הפרות לכל אחד ממתקני הרפת (רובוט, מאביס תערובת, פס האבסת בליל, תאי רביצה, שקתות מים וכ"ו) נגזרת ממודל סטוכסטי וניתנת ליצוג על ידי הסתברות אקספוננציאלית, נורמלית, לוג-נורמל, ו-וייבול (weibull) .

II) הרפת הרובוטית כמערכת ניתנת לניסוח מתמטי כמודל רשת תורים (בדומה לרשת תקשורת מחשבים). הרפת מכילה מספר מתקנים, הפרות צריכות "לקבל שרות" במתקנים הללו, כשפרה סיימה לקבל שרות במתקן x היא ממשיכה למתקן y. הקשר בין x_i ל- y_i נקבע על ידי מטריצת מעברים (Transition matrix).

III) מהתבונות במטריצת המעברים ניתן להסיק שב- 90% מהמקרים הפרות מבקרות במאביס תערובת מיד אחרי הביקור ברובוט. לכן, מאביס תערובת (בפני עצמו או בתוך הרובוט) הוא כלי אפקטיבי לאכוף כמות ביקורים מספקת ברובוט. בנוסף, מטריצת המעברים מצביעה על תנועה רבה בין אזור פס האבסה לבין אזור תאי רביצה ובין פס האבסה לשקתות המים. אם שערי הכוונה מונעים כיווני תנועה אלו (forced routine) - עלול להיגרם עומס (stress) על הפרה ופגיעה בצריכת מזון.

IV) זמני האבסת בליל מהווים גורמים דומיננטים בהתנהגות הפרות ומשפיעים על כלל ביצועי המערכת - זמני ושיטת האבסה צריכים להיות חלק אינטגרלי מהמודל.

V) תפוסת תאי הרביצה מעולם לא עלתה על 75% ממספר הפרות ברפת - יתכן ואפשר לבנות פחות תאי רביצה ממספר הפרות ללא פגיעה בדפוסי התנהגות של הפרות.

VI) נצילות הרובוט בשני המשקים המסחריים שהשתתפו בניסוי הייתה יחסית גבוהה (כ- 85% לאורך היממה) ויכולות הצמדת (attachment) גביעי החליבה בהחלט משביעת רצון (כשל הצמדה רק כ-

תכנון רפת רובוטית - מודל, סימולציה ואופטימיזציה

תקציר

בימים אלו, כאשר מספר משקי החלב הולך ויורד, אלו הנשארים בענף גדלים מבחינת היקף ואוטומציה. אחת האפשריות לאוטומציה היא קניית רובוט חליבה. לרובוטים אלו השפעה על שגרת העבודה וכמות העובדים ברפת, תנובת חלב, התנהגות הפרות, ממשק האבסה, תכנון מבני הרפת ושיטות ניהול. כל האספקטים הללו צריכים להילקח בחשבון כאשר מתכננים רפת רובוטית.

ברפת המסורתית, תכנון המבנים ומיקומם מושפע משימוש במכון חליבה, כאשר מחליפים את המכון ברובוט - תכנון הרפת צריך להשתנות בהתאם לתפיסת הניהול של רפת רובוטית. תפוסת הרובוט (ולכן גם תנובת הפרות) תלויה בתדירות גישת הפרות לרובוט (2,3,...,6 חליבות ביום). המערכת המשקית צריכה לתמוך ולעודד גישת הפרות לרובוט, הן על ידי תכנון פיזי של מבני הרפת, והן על ידי שיטות ניהול, ממשק האבסה וכ"ו. מספר הפרות, מספר הרובוטים, מספר מקומות האבסת בליל (אורך פס האבסה), מספר מאביסי תערובת, וגודל השטח לפרה הם שיקולים חשובים בקביעת תכנון הרפת (Layout). מטרת התכנון האופטימלי למצוא נקודת איזון בין נצילות מתקני הרפת ל-"תנאי החיים" או "רווחת הפרה" (animal welfare). במילים אחרות, הפרמטרים לאופטימיזציה הם, מחד, הצורך הכלכלי לנצילות גבוהה של מתקני הרפת כנגד הרצון למנוע היווצרות תורים והתנהגות אגרסיבית בין הפרות. אולם, הנצילות המעשית של כל מתקן ברפת (רובוט, מאביס תערובת, פס האבסה וכ"ו) תלויה בנגישות התאורטית והגישה בפועל של הפרות למתקנים השונים. שני הגורמים הללו תלויים בשיטת הניהול ובתכנון המבנים ברפת הספציפית. בנוסף, יש שונות גדולה בין רפתנים ותנאים מקומיים לכן הפתרון האופטימלי מתקיים עבור רפת מסוימת, קרי לכל רפת יש לבצע את החישוב (אופטימיזציה) מחדש. תכנון רפת הוא נושא רב-תחומי הדורש ידע מגוון בעל אספקטים שונים. יתר-על-כן, רובוטים הם פיתוח טכנולוגי חדש. יחסית למכוני חליבה, למתכנן רפת רובוטית יש מעט ניסיון מעשי שניתן לגזור ממנו השלכות לתכנון. לכן, יש צורך ברור בשיטת תכנון המבוססת על חוקים אובייקטיבים שנמדדו בצורה מדעית, התנהגות הפרות, מבני רפת קיימים, ממשק האבסה, שיטות ניהול ופרמטרים הניתנים להתאמה אישית לכל רפת או רפתן.

שיטת התכנון החדשה צריכה להיות מיושמת ככלי מעשי (תוכנת מחשב) שתתאים למהנדס, חוקר, רפתן, מדריך, יועץ או יצרן רובוטים. מטרת מחקר זה הייתה לפתח כלי תכנוני שיאפשר תכנון רפת רובוטית אופטימלית. סימולציה מאפשרת בחינת הפתרון לפני שבונים בפועל אפילו קיר אחד. הפתרון האופטימלי צריך להיות מותאם לתנאים המקומיים של כל רפת ושיטות הניהול של כל רפתן אולם השיטה צריכה להיות ישימה בכל מקום.

המחקר תורם בשלושה כיוונים: (1) פיתוח שיטה מדעית לתכנון רפת רובוטית הלוקחת בחשבון את כל האספקטים המשפיעים ישירות על התכנון. כגון המבנים שכבר קיימים ברפת, התנהגות הפרות, שיטות ניהול, פוטנציאל יצור, נצילות מתקנים, ממשק האבסה והאנטרקציות ביניהם, (2) יישום השיטה החדשה, על-ידי פיתוח ממשק משתמש ידידותי - כלי תוכנה המשמש לתכנון הרפת, בשלבי הקמתה ושדרוגה כאשר הרפת כבר קיימת, (3) הטמעת השיטה החדשה באמצעות הצגת דוגמאות, הצגת פתרון אופטימלי והצגת

תכנון רפת רובוטית - מודל, סימולציה ואופטימיזציה

תכנון רפת רובוטית - מודל, סימולציה ואופטימיזציה

אילן הלחמי