Operational efficiency of incorporating a novel robotic rotary into a pasture-based dairy farming system

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Operational efficiency of incorporating a novel robotic rotary into a pasture-based dairy farming system

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This thesis is dedicated to my little Nephew

Arjan Hendrik

What the heart has once known, it shall never forget

Preface

This thesis is comprised of five Chapters of which four have been written in manuscript style. Chapter 3, Chapter 4 and Chapter 5 have been submitted for publication. All three publications have R. Kolbach as the primary author.

I herby certify that this thesis comprises only my original work and that I have not used any other sources or aids other than those declared or acknowledged. All passages, Figures and Tables of this work which I have quoted are clearly marked.

This thesis has not been submitted in any previous application for a degree nor is it currently being submitted for another degree elsewhere.

René Kolbach

March 2012

Abstract

The thesis presents an original investigation into the feasibility and operational efficiency of a novel prototype robotic rotary (RR) incorporated into a low-input, pasture-based Australian dairy farming system. A world's first high throughput automatic milking system was installed, co-developed and tested at the Elizabeth Macarthur Agricultural Institute site (Camden, NSW, Australia). Being the first farm internationally to tackle voluntary distributed cow traffic (cf. batch milking) the challenges and learnings were specific to the system utilisation and the stage of technological development of the Camden installation. The thesis focuses on the challenges associated with application of the technology, of which learnings will have an immense level of importance for the first commercial installations on farm and further development of the system. These challenges were; (1) investigating a coping mechanism (with and without extra feed) to ensure and maintain high quality milk collection and storage for periods of underutilisation of the systems' capacity (with voluntary cow traffic) in the absence of an automatic plant cleaning function, (2) understanding the impact of premilking teat preparation on the incidence of unsuccessful milkings, to ensure that farmers make an informed decision prior to commencement of the RR (as purchase of the teat preparation module will be optional), and (3) potential implications of management strategies for incompletely milked cows on dairy layouts. During periods of underutilisation the operator can deactivate a proportion of bails to better match the demand and availability of milk harvesting bails. Thus, investigations were conducted to understand the impact of bail activation sequence, availability of feed and cow queue size on voluntary cow traffic and robotic throughput efficiency. It was found that overall the availability of a feed reward as cows entered the RR had a larger effect on cow traffic than bail activation sequence, although the number of cows present (voluntarily) at the yard also played a role. Furthermore, having a greater number of consecutive bails activated resulted in more robot operations being conducted simultaneously resulting in an increased harvesting efficiency. Premilking teat preparation is also known to impact on milk harvesting efficiency, and as this component of the technology will be optional an investigation was conducted to assess the effects of not using a premilking teat preparation device on attachment accuracy and milk removal characteristics. The teat cup attachment was more successful and faster when cows were subjected to the teat cleaning treatment. Cows milked after being exposed to teat cleaning treatment, with a short milking interval (< 8 h), had a higher peak milk flow, however no difference was observed in the average milk flow rate of individual cows. Whilst there was an impact on attachment success by the use of the premilking treatment, the overall level of success was still lower than desirable. With this in mind a study of different management practices of incompletely milked cows was conducted. The system showed no difference in attachment success between milking incomplete cows after a one- or three-hour interval. This suggested that there is a level of flexibility available in designing the dairy layout and that no significant advantage or disadvantage (with regard to subsequent success level) exists in drafting incomplete cows directly back to the pre-milking yard compared to offering them an opportunity to spend time on a feedpad prior to the second attempt. The results presented in this thesis will be invaluable in furthering industry understanding of management practices with the new milk harvesting technology, the RR. The contribution of these scientific investigations will be extremely important to the success of the development of the system, which is progressing closer to commercialisation.

Acknowledgements

Whilst this thesis is a product of 2 years of my work, there are many people that have contributed, in different ways, to make it possible.

I wish to thank, first and foremost, my supervisor Dr. Kendra L. Kerrisk who has always helped me from the very first moment of this project. I appreciate all her invaluable contributions of time, ideas, and guidance to make my research experience one to never forget. I have been largely motivated by the joy and enthusiasm she has for her research. I am also grateful she was an enormous personal support to me, even outside the university walls with her husband Brent and their sons Jacob and Thomas. I am very delighted that they 'adopted' me and made me part of a big family.

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This thesis would not have been possible without the work done by the staff of the AMS farm. To Shannon Bennetts, Grant Oldfield and Terry Osborne; I am thankful for their support during my studies and stay in Australia.

The support of Mikael Karttunen has made it possible to continue to research the AMR™. Without his huge efforts, input of time and persistency this project would not have been possible. I am also extremely grateful to Kattis Karttunen and the rest of the DeLaval project team. It has been a delight to work as one of the first students on the world's first high throughput automatic milking system.

To the Australian national research project, FutureDairy, the team and its major sponsors, Dairy Australia, DeLaval, NSW Department of Primary Industries and The University of Sydney, who gave me the opportunity to be part of such a ground-breaking research project.

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To all my “cycling mates” Down Under, who have contributed to a great period of my life. I would like to acknowledge in particular the friendship of the Bush family, Matt & Tash and Paul & Toni and Colin Grimes. I have really appreciated the great hospitability and support they gave me. Likewise, thanks to Nick, Conor, Paul and Daryl for the many bike rides and coffee breaks.

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The experience in the last years has made me ready for the next journey in life, thanks to all of you.

Thank you!

René Kolbach
The University of Sydney
March 2012

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Glossary of abbreviations

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
ACA	Automatic Cup Attacher
AMR™	Automatic Milking Rotary
AMS	Automatic Milking System
AU$	Australian Dollar
b	Beta
CMS	Conventional Milking System
DIM	Days In Milk
DM	Dry Matter
EMAI	Elizabeth Macarthur Agricultural Institute
fl.	Dutch Guilder
GLMM	Generalised Linear Mixed Model
h	Hour(s)
HBR	Herringbone Rotary
HY	Holding Yard
IRR	Internal Rate of Return
kg	Kilogram
Lact.	Parity
LB	Left Back quarter
LF	Left Front quarter
m	Minute(s)
MF	Milking Frequency
MI	Milking Interval
MP	Milk Point (on the RR platform)
NFF	National Farmers' Federation
NPV	Net Present Value
NSW	New South Wales
OT	Oxytocin
PMR	Partial Mixed Ration
RB	Right Back quarter
REML	Restricted Maximum Likelihood

RF	Right Front quarter
RFI	Room for Investment
RR	Robotic Rotary
s	Second(s)
SD	Standard Deviation
SE(b)	Standard Error of beta
STO	Step Time Out
t	Tonne
TMR	Total Mixed Ration
ToF	Time of Flight
TPM	Teat Preparation Module
TSM	Teat Spray Module
US$	American Dollar
VMS™	Voluntary Milking System
yr	Year(s)
%	Percentage
®	Registered Trademark
™	Unregistered trademark
°C	Degrees Celsius
α	Alpha
€	Euro
°	Degree (angle)

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General introduction

General introduction

The Australian dairy industry is pasture-based with 98% of farms sourcing at least a portion of feed from grazed pasture in 2009–2010 (Little 2010; Dairy Australia 2010b). Grazed pasture is generally recognised as the cheapest feed source for dairy cows (Dillon 2005), giving Australia the advantage of producing at a relatively low cost compared to many international industries. Most large dairy producing countries around the world, have a long term trend of a decreasing number of dairy farms albeit with a relatively stable national dairy herd size (i.e. less farms with more cows per farm; Koopstra 2011), Australia is no exception.

As a result of the high labour costs on farms, in the mid seventies automatic milking systems (AMS) were developed and introduced in European counties in the early nineties (de Koning et al. 2002; Svennersten-Sjaunja and Pettersson 2008). Recent data have shown that over 11,000 farms in more than 25 countries worldwide use AMS (de Koning 2011a). A considerable amount of research has been conducted around AMS, however the majority of the research was carried out in indoor systems, rather than within grazing systems as those common in Australia. To investigate the feasibility of integrating AMS into a pasture-based dairy farming system the Greenfield project (Hamilton, New Zealand) and the FutureDairy project (Camden, NSW, Australia) were established (in 2001 and 2005 respectively). These projects have unequivocally demonstrated that AMS can be successfully integrated into pasture-based farm management systems with voluntary and distributed cow traffic.

Whilst there are large-scale AMS installations globally, it has become evident that the current AMS technology will be unlikely to have widespread adoption within large herds (> 500 cows) due to the relatively high capital cost (per cow) of AMS in comparison to conventional milking system installations (Alford et al. 2010). However, with the growing demand of labour and the increased interest in automation (and its benefits) in the dairy industry a new technology has been developed with the concept being launched in anticipation of commercialisation during 2012. In September 2010, DeLaval (Tumba, Sweden) introduced the world's first high throughput AMS, a robotic rotary (RR), the automatic milking rotary (AMR™, Rosengren 2010a, b). The RR is theoretically capable of milking 50 to 90 cows per hour depending on the installation (with either two or four robots) and the farm system management strategies.

Whilst a substantial amount of research has now been conducted and reported around the established AMS technology, the RR is a new piece of technology which has not been studied previously. System performance of the RR can only be benchmarked in relation to the system performance of published single- and multi-box AMS technology. This thesis is the world's first reporting on the feasibility and operational efficiency of the RR.

In AMS, cow traffic can impact on the feasibility and operational efficiency of the system and has been highlighted by many researchers around the world as a key factor affecting the success of an AMS installation (Prescott et al. 1998a; de Koning et al. 2002; Jago et al. 2002; Davis et al. 2007; Halachmi et al. 2009; Utsumi 2011). Similarly, key factors affecting the RR's feasibility and operational efficiency are also related to the number of cows presenting themselves to the rotary entrance; and in addition its relationship with the number of active milking bails at any given time, the operational functions of the robotic arms (e.g. washing or not washing) and the management of incomplete milked cows.

The general aim of this thesis is to increase our understanding of the feasibility and operational efficiency of a novel prototype RR in a low-input, pasture-based Australian dairy farming system. The potential throughput, performance and limitations have been evaluated for the world's first high throughput AMS.

After a review of the relevant literature (Chapter 1), the functioning and first-hand experiences of the RR are presented (Chapter 2). These experiences helped to define a number of challenges, arising from operating the system with voluntary cow traffic. No other test farms have operated in this manner so all other experiences with the technology have involved batch milking. The results of this investigation have shown that whilst the RR is operational in a voluntary fashion, the system utilisation is reduced at specific times during the day. To ensure the collection and storage of high quality milk is maintained, particularly during these periods of underutilisation, a strategy had to be devised to cope with this utilisation challenge and the associated plant hygiene (Chapter 3). These coping mechanisms are particular to the RR (as opposed to AMS) as a result of the absence of an automatic plant cleaning function. The need was also largely created by the specific conditions associated with operating the system with voluntary cow traffic and would likely be relevant during periods of low utilisation on both a daily and seasonal basis (particularly with fluctuating herd sizes). The hypothesis being that a consecutive bail activation sequence and the presence of in-bail feeding would result in improved cow traffic and in more efficient robot operation, thereby improving the overall potential and actual throughput and the milk harvesting rates of the RR.

As the RR becomes commercially available farmers will need to be informed of the function of components of the RR; particularly where knowledge level is likely to impact on decisions to install (or not install) optional components and configuration of dairy layout. One such optional component is the premilking teat preparation (Chapter 4). It was hypothesised that using the teat preparation module will result in a higher attachment accuracy and speed (time needed for attachment of four teat cups) and will increase milk flow, thereby lowering the cups on time and improving the potential and actual throughput and milk harvesting efficiency of the RR.

And finally, as it was found that the success levels of teat cup attachment on the prototype RR were lower than desirable, potential management strategies and their implications for incompletely milked cows on dairy layouts were investigated and reported in Chapter 5. It was hypothesised that the extension of the interval between two attempts for milking would increase the attachment success rate of previously incompletely milked cows. It was expected that with a shorter milking interval between the two milking attempts, attachment of milking cup(s) to the unmilked teat(s) would be more challenging due to the increased flaccidity and proximity of the teats.

Overall, this thesis is comprised of three research Chapters, all written in manuscript style and submitted for publication in various international journals. Finally, the thesis is completed by a general discussion and conclusion of the main findings from each of the Chapters and their implications for the dairy industry.

Chapter 1. Review of the literature

Review of the literature

1.1. Introduction

Targeted improvement of labour productivity is a widely observed trend around the world. This has been aligned with a widespread uptake of automatic milking systems (AMS) in many countries where suitable skilled labour is expensive and difficult to source. This review of the literature encompasses four major areas around Australian dairy farming systems and AMS. The aim of this study is to contextualise the Australian dairy industry and the importance of capacity and efficiency aspects of AMS. Firstly an overview of the dairy industry is presented, showing that the majority of the farms are pasture-based which is named as a key driver for profitability. This is followed with an introduction into the AMS used around the world. The capacity, premilking teat preparation strategies and attachment accuracy of existing commercial technologies is presented since it provides the most relevant benchmarks for technology performance in absence of published data specific to the robotic rotary (RR). Emphasis is then place at the economical viability of the AMS around the world and in Australia in particular, affected by a change in labour and productivity of the dairy herd. Finally the literature review reflects, as the AMS is a voluntary based system, incentives used to realise cow traffic towards the AMS and pasture-based AMS systems with voluntary cow traffic. In a pasture-based system the incentives are of great importance, predominantly due to the fact that the cows have to walk a greater distance to the system (compared to housed cows).

1.2. Australian dairy industry

1.2.1 Physical and financial situation

Recent data of the Australian Bureau of Statistic (ABS 2010) show that there were 7,749 dairy farms in Australian in 2009–2010. It was noted that a decrease of 12% was observed in the total number of farms between 2007–2008 and 2008–2009. A reduction (in the number of farms) of 40% has occurred since 1999–2000 when there were 12,896 farms and a 65% reduction over the past two decades from 21,994 farms. The reduction in the number of farms operational is observed internationally and the trend in the last ten years is presented in Table 1.1 (Koopstra 2011). Reduced price support and changing business practices have inadvertently encouraged the growth of farm businesses towards larger, more efficient operating systems (Dairy Australia 2009), this trend within Australia is shown in Figure 1.1 (Dairy Australia 2011). Victoria is home to the largest number of dairy farm businesses with 4,939 farms, followed by New South Wales with 1,016 farms. However, alongside the decrease in the number of farms, the number of dairy cattle increased by 3% in 2008–2009 to 2.6 million (including young stock and bulls) and the number of milking cows (including dry cows) increased by 2% to 1.7 million head (ABS 7121.0 2010). Figure 1.2 shows the major dairy areas of Australia (Dharma and Martin 2010).

Table 1.1: Global trend; decreased number of farms with increased number of cows per farm among high milk producing countries in the world (Koopstra 2011)

Country	Number of	2000	2005	2008	2010
Australia	Farms	11,800	9,200	7,900	7,500
	Cows/farm	183	202	212	213
United States	Farms	105,200	78,300	65,000	62,500
	Cows/farm	88	116	142	146
Netherlands	Farms	29,500	23,500	20,300	19,800
	Cows/farm	51	61	74	75
Germany	Farms	129,900	108,000	94,100	90,400
	Cows/farm	35	39	44	46
Denmark	Farms	9,700	5,900	4,100	3,900
	Cows/farm	66	94	140	147
Sweden	Farms	12,200	8,600	6,400	6,400
	Cows/farm	35	45	55	55
Argentina	Farms	17,000	13,500	11,000	11,000
	Cows/farm	144	156	191	191
New Zealand	Farms	13,900	12,200	11,600	11,700
	Cows/farm	251	336	396	415

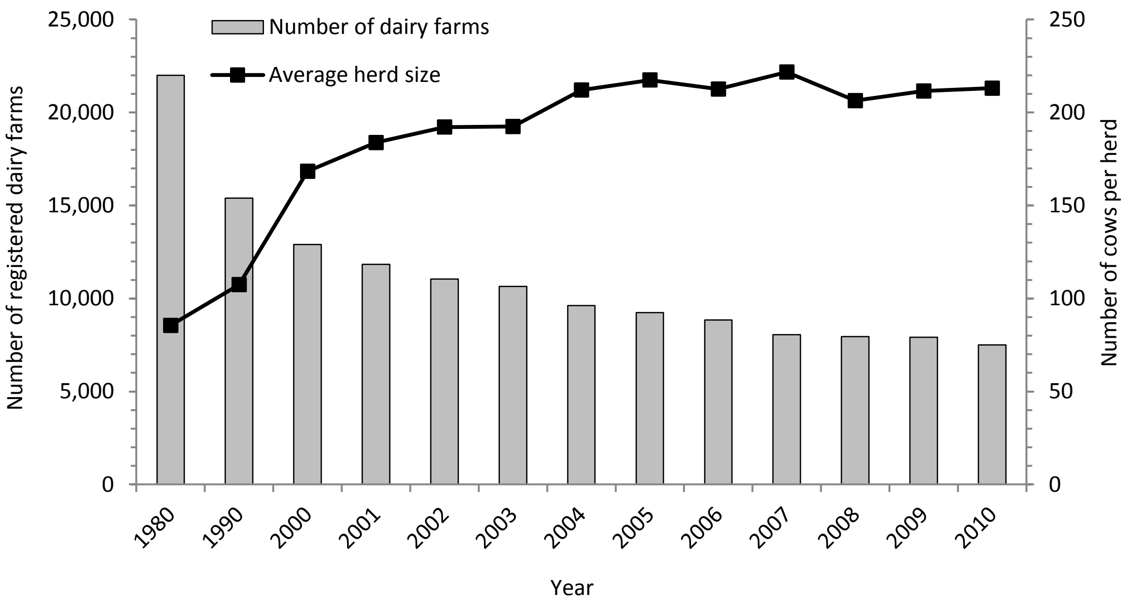

Figure 1.1: Number of registered farms and number of dairy cows per herd (Dairy Australia 2011)

An overview of the financial performance of Australian dairy farms by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES 2010) published physical and financial averages per farm (Table 1.2). The reduction in cash income is largely explained by a decrease in milk price. The drop in cash income between 2007–2008 and 2008–2009 was explained by a decreased milk price in conjunction with an increase of the total operational cash cost (+6%). The increased cash cost was largely due to increased fodder prices (as a result of the drought) and an increase in interest payments (caused by to larger debts). The average farm debt is estimated by ABARES (2010) at a level of AU$683,000, which is 20% higher than figures reported two years ago, indicating the negative impact of a change in milk price and feed cost on the dairy industry.

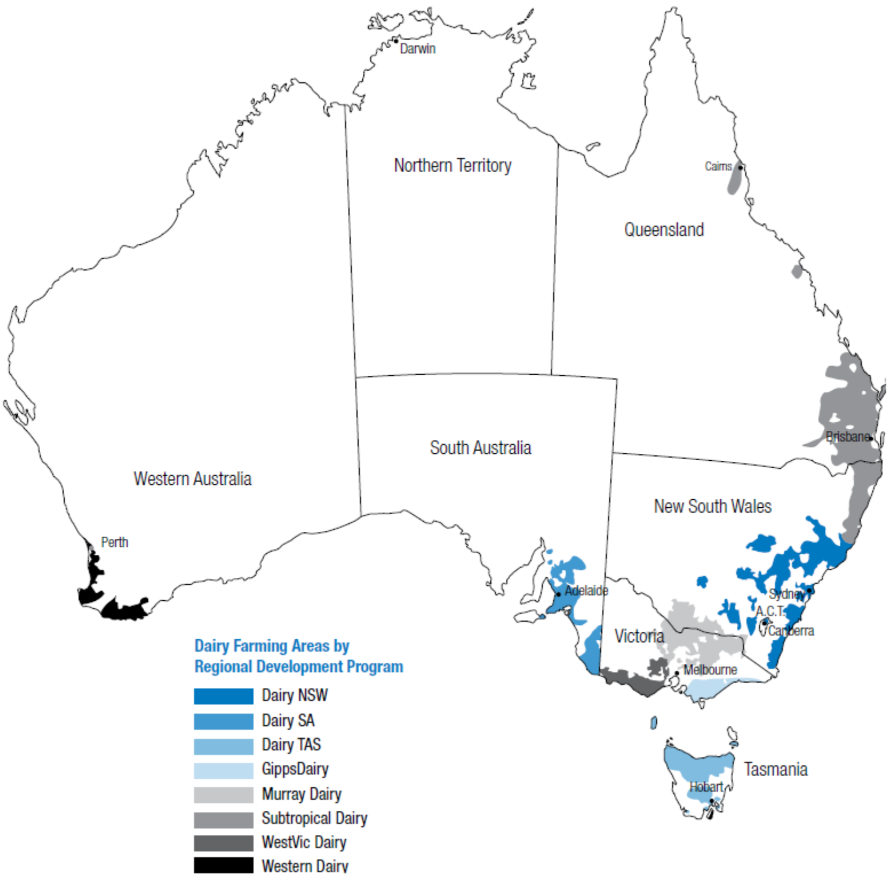

Figure 1.2: ABARE, major Australian dairy farming regions (Dharma and Martin 2010)

Table 1.2: ABARES, Physical and financial estimates–Australian dairy farms (average per farm; Dharma and Martin 2010)

Indicator	1999–2000	2001–2002	2007–2008	2008–2009	2009–2010	2010–2011
Area of operation (ha)	226	257	252	264	249	236
Cows per farm (at 30 June)	256	257	334	342	340	336
Max number of cows milked for 3 months	165	197	202	212	204	205
Milk production (kg)	805,176	994,404	1,136,920	1,247,300	1,204,800	1,227,000
Milk production per cow (kg)	4,805	4,881	5,630	5,900	5,900	6,000
Cash income (AU$)	68,304	112,810	129,310	88,000	77,300	100,000
Farm business profit (AU$)	3,904	60,880	65,830	6,700	-1,400	5,000

The dairy industry is Australia's third largest rural industry behind the beef and wheat industry (Dairy Australia 2009; ABS 7121.0 2010). In 2008–2009 the total gross value of whole milk amounted to a total of AU$3,987.6 million and the total gross value of Australian agriculture products was AU$41,800 million. On average 45% of the total annual milk produced is exported, predominantly to Japan (20% of the total exported value), with a total value of AU$2,900 million (National Farmers' Federation 2009). Australia accounts for 11% of the world trade in dairy products, exceeded only by New Zealand (33%) and the European Union (32%; NFF 2009).

1.2.2 Feeding system(s)

The Australian dairy industry is pasture-based. Grazed pasture provided at least a proportion of the feed base on 98% of the dairy farms in 2009–2010 (system 1 to 4 as indicated below). Pasture-based systems are widely accepted as having the least expensive feed source (Dillon 2005), giving Australia the advantage of producing high-quality milk at a relatively low cost of production (Figure 1.3). Dairy Australia uses a standard classification that classifies the farms based on their feeding strategy and can generally be split into five main feeding systems (Little 2010; Dairy Australia 2010b), namely:

1. Grazed pasture + other forages + up to 1.0 tonne grain/concentrates fed in bail
2. Grazed pasture + other forages + more than 1.0 tonne grain/concentrates fed in bail
3. Pasture grazed for most, or all of the year + partial mixed ration on feed pad with or without grain/concentrates fed in bail
4. Hybrid system with pasture grazed for less than nine months per year + partial mixed ration (PMR) on feed pad with or without grain/concentrates fed in bail
5. Total mixed ration system (TMR) with zero grazing. Cows housed and fed total mixed ration.

Figure 1.4 shows the proportion of Australian farmers using the five main feeding systems. System 5 was predominantly used in Queensland and South Australia, 100% grazing was used in 20% of the Tasmanian dairy farms. As shown, system 2 was the most prevalent system used across Australia. On average 1.58 tonnes of grain/concentrates were fed per cow/year nationally (Little 2010; Dairy Australia 2010b).

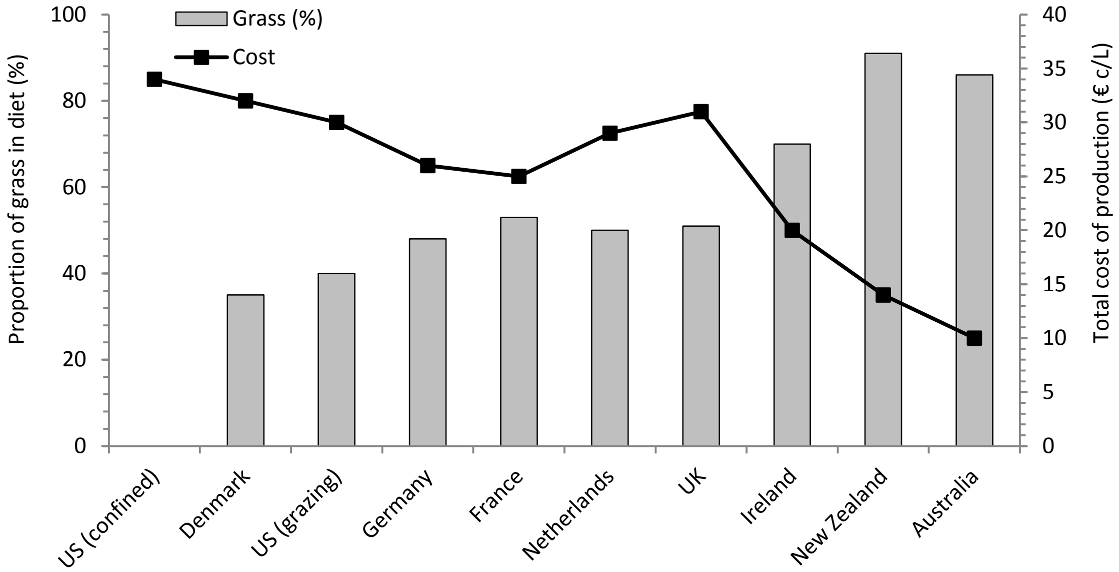

Figure 1.3: Total cost of milk production (€ c/L) in relation to proportion of grazed grass in the diet among high milk producing countries in the world (redrawn from Dillon, 2005)

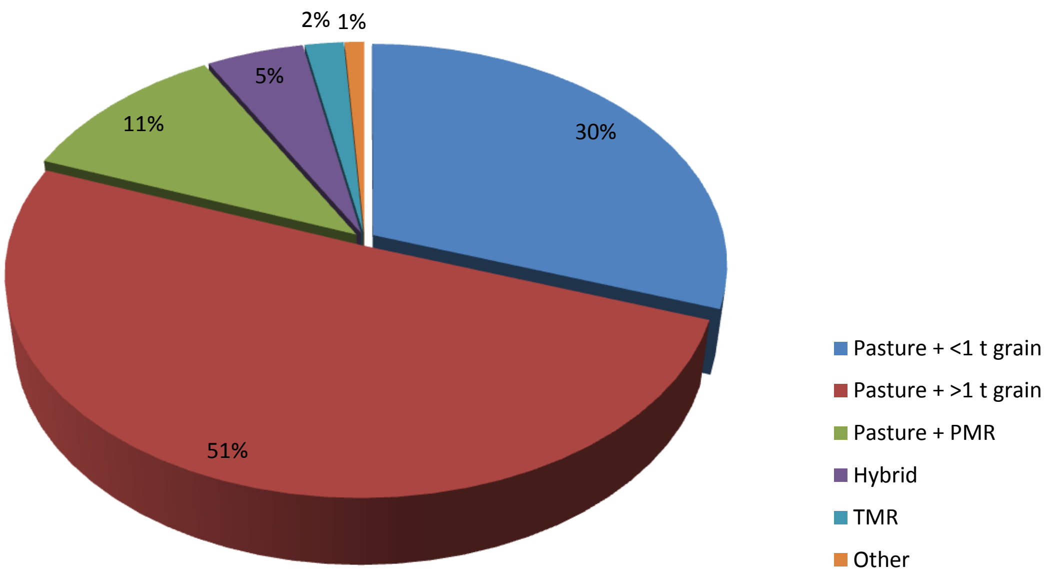

Figure 1.4: Proportion of farmers using the five feeding systems across Australia. TMR = total mixed ration; PMR = partial mixed ration (Dairy Australia 2010b)

1.2.3 Labour

About 40,000 people are reported to be employed directly on dairy farms and manufacturing plants across Australia (Dairy Australia 2009). In addition to the direct hired labour there is a much larger level of employment in support and service sectors (e.g. transport, distribution activities, consultants, feed supply merchants etc.). The national dairy farmers' survey showed that in 2010 the number of farms operated by only one person, or with a partner, was declining. In 2007, 43% of the farms were operational as family farms but this figure was reduced by 15%

in 2009. In Australia 61% of the farms attracted paid employment, this ranged from 48% in Western Victoria to 90% in the Bega region (Dairy Australia 2010a). This high reliance on hired labour impacts significant on operating costs.

As in any dairy country around the world, feed and labour account for a major part of the cost of producing milk in Australia. Labour cost (hired and family labour) accounted for about 20% of the total cost of producing milk in the years 2009–2010 (Dharma and Martin 2010). Labour and feed costs combined together explain 47% of the operating cost on farm. A review by García and Fulkerson (2005) pointed out the likely issues related to employed labour in the near future on farm. Efficiency of labour utilisation, a combination of management of labour and availability of skilled employees, will be an issue which is recognised to effect further growth of Australian dairy farms. This will be one of the key drivers for changes made during expansion of the dairy industry. Farmers will likely attempt to decrease the labour costs with increased productivity per labour unit by increasing the herd size whilst maintaining or even decreasing the labour pool on farm. Attracting and retaining skilled available labour is expected to be an ongoing challenge as long as the conditions of work are perceived to be poor and the hours of work within the dairying sector are associated with a decreased lifestyle compared to other industries (García and Fulkerson 2005). As milk harvesting is the largest single component of labour on farm, a considerable amount of work is conducted in improving milking management and milk harvesting efficiencies. The potential exists for adoption of AMS to have a significant impact on attracting and retaining employed labour and on improving efficiency of labour utilisation.

1.3. Automatic milking system

1.3.1 General

In the mid seventies the increase of labour cost in several countries resulted in the development of automation of many components of the time consuming activity, milk harvesting (de Koning et al. 2002; de Koning 2010). It took a decade before the first prototypes of fully automatic milking where sufficiently capable and reliable to milk cows. The “automatic milking system” (AMS) is able to milk cows without direct human supervision. The AMS automates all the steps of the milking process, teats are located and cleaned, teat cups are attached, teats are sprayed with disinfectant and cows get an individual measured allocation of concentrated feed. Whilst these are the basic tasks, the functionality of the technology is much broader and encompasses tasks including (but not limited to) diverting milk from individual cows, plant and equipment cleaning, reporting on machine and animal parameters and monitoring milk quality components. Within an AMS extra emphasis is placed on the motivation of the cows to be milked in a self-service manner more times a day (Rossing et al. 1997; de Koning and Rodenburg 2004). The 'self-service' or "voluntary" milking is necessary to ensure that cows are not waiting for milking for extended periods as throughput rates are dramatically lower than those achieved by human operators.

In 1992 the first AMS was implemented in the Netherlands. The first systems were installed on family farms, with 50 to 150 dairy cows, as a response to the high labour cost (de Koning et al. 2002; de Koning and Rodenburg 2004; Svennersten-Sjaunja and Pettersson 2008). A study of Hogeveen et al. (2004), with 60 farmers who had recently invested in AMS, showed that the motivation for investment was mainly related to the need for a reduction in labour, improved labour and lifestyle flexibility and the possibility to milk more than twice a day. Economical consequences and social factors both played a major role in deciding whether to invest in AMS or not. At the end of 2003, worldwide some 2,200 commercial farms were using one or more AM-systems to milk their cows (de Koning and Rodenburg 2004). In some of the European countries, 50 to 60% of the newly installed milk harvesting equipment is automatic (Davis et al. 2008b; Lassen et al. 2012). Currently, approximately 11,000 farms in over 25 countries worldwide use AMS to milk the dairy herd (de Koning 2011a). In recent years there have been a number of new AMS farms commissioned in Australia with installations occurring in Queensland, New South Wales, Victoria, South Australia and Tasmania. There are currently 16 AMS farms operational in Australia (Kerrisk 2012, pers. comm.). The rapid increase in the number of farms with AMS across the globe is shown in Figure 1.5, with Figure 1.6 showing the AMS adoption curve in Australia.

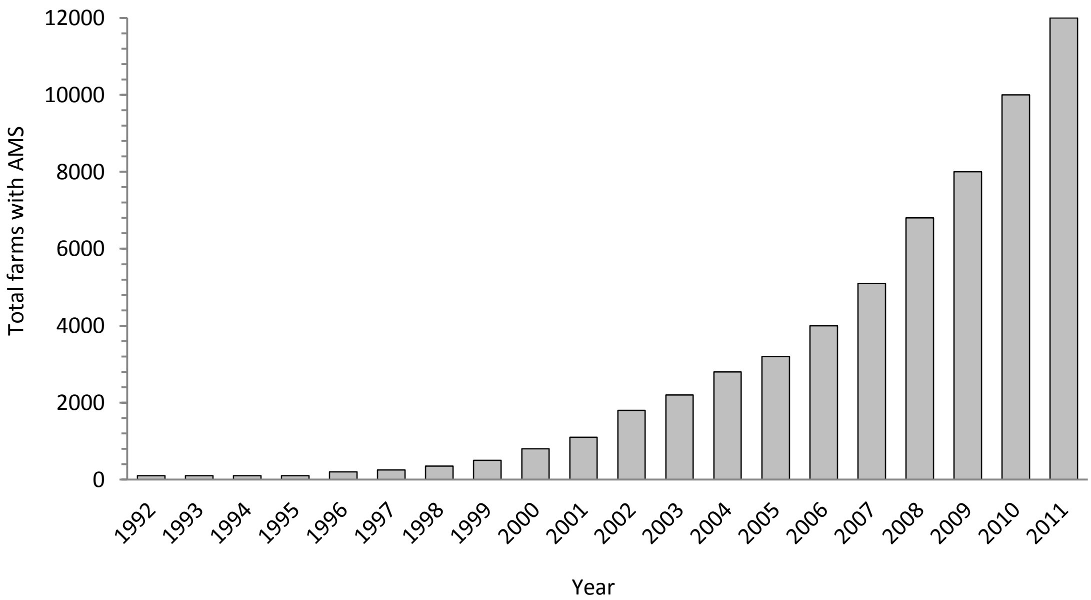

Figure 1.5: Cumulative AMS farm installations world wide (de Koning 2011a)

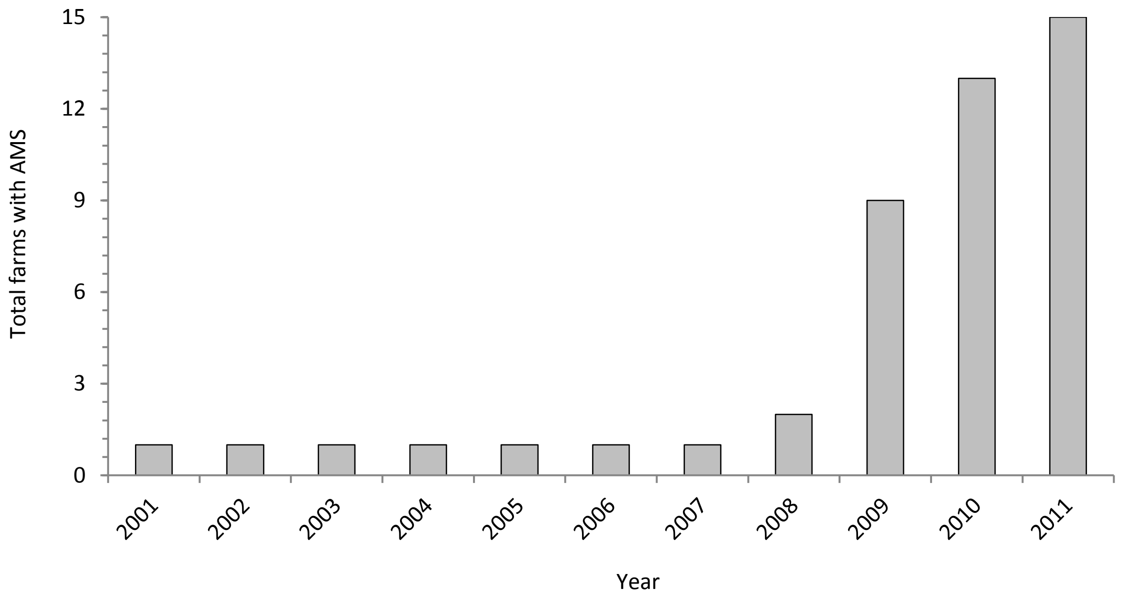

Figure 1.6: Cumulative AMS farm installations in Australia (K.L. Kerrisk, pers. comm.)

Today it is very evident that an AMS can be effectively incorporated into an indoor system. However, the majority of Australian dairy farm systems are outdoor and pasture-based. In an outdoor pasture-based system, the cows need to voluntarily move around the farm to be milked in the AMS. The most reliable motivator for the generation of “voluntary cow traffic” is the provision of food incentives for encouragement. This is a very important factor that has to be managed if farmers are to realise a high AMS utilisation rate. By giving the cows two fresh breaks of grass per day, the cows are forced to leave the paddocks to be milked at least once a day (Davis et al. 2007). Pasture allocation (size, timing and frequency of allocations) is the key factor affecting milking frequency and AMS utilisation in Australia. Work conducted by Lyons (2011) quantified the impact of provision of two versus three pasture allocations which resulted in increases in cow traffic, milking frequency and milk production. Regular and reliable cow traffic is important since the true benefits of AMS are eroded when cows have to be fetched from the paddock regularly. It would be a disadvantage if labour needed in the dairy for milking were replaced by labour needed for fetching cows (Davis et al. 2007).

Whilst widespread AMS adoption has not occurred in Australia yet, it does not mean that technologies have been disregarded by the industry. When machine milking were introduced, in the 1940s, Australia had a higher adoption rate (Janson 1973), compared to the counties currently having a high number of AMS commissioned (e.g. the Netherlands and Denmark; Figure 1.7). This shows that Australian farmers are willing to make investment when the technology is recognised to be suitable for their dairying system. According to the 2008–2009 Australian Bureau of Agricultural and Resource Economics (ABARE) report on technology and management practices within the Australian dairy industry (Mackinnon et al. 2010), the main technologies currently incorporated on farm are; backing gates, vat cleaning systems, cup removers and teat sprays. It was also reported that almost 90% of farms utilise a computer for financial reasons, whilst 65 to 70% of farms use them for management of milking or breeding records. Technology is adopted and incorporated on Australian dairy farms; the question will be, not if, but when farmers, after a slow introduction, start to adapt AMS technology at a rate that has being observed in other countries around the world.

It would be interesting to follow farmers attitudes toward AMS in the industry surveys that are carried out periodically. In a 2004–05 survey 2% of surveyed farmers responded that they expected to adopt AMS in the next 12 months (Lubulwa and Shafron 2007) and in 2008–09 a similar figure of 3% was reported (Mackinnon et al. 2010). There doesn't appear to be any industry data indicating how many dairies are likely to be replaced in coming years or the average age of existing dairies. However the ABARE report (2010) indicated that 19% of surveyed farmers who intended to change their current technology were intending to conduct dairy improvements within the following 12 months.

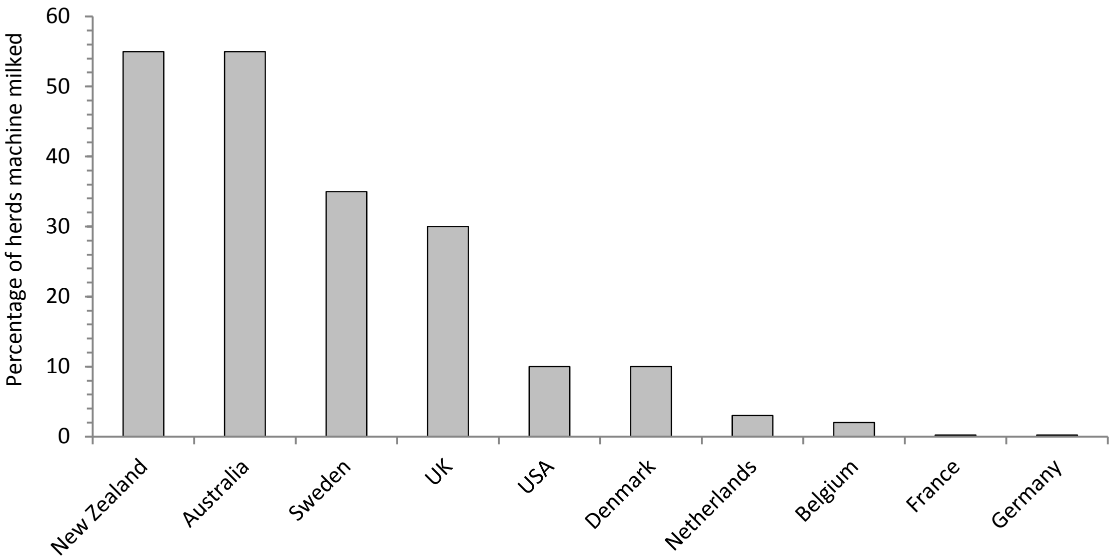

Figure 1.7: The global use of milking machines at the beginning of the 1940s (Janson 1973)

1.3.2 Capacity

With the current, single- and multi-box, AMS technology the capacity of the robot is a limiting factor affecting how many cows can be milked. In the early 2000s it was reported that about 45 to 60 cows could be milked with one, single-box, AMS (Schick et al. 2000; de Koning and Rodenburg 2004). Recently a study showed that the cow to robot ratio can be increased from 60:1 to 80:1 with an occupation rate (time AMS available for milking per 24 h) of 85% (Andre et al. 2010). A study conducted in New Zealand showed that with relatively low producing cows, 92 cows could be milked per day, pushing AMS utilisation in terms of milk harvested per day (kg), through manipulation of both milking frequency per cow and ratio of cows per AMS (Jago and Burke 2010). However, their study, conducted in a pasture-based system, achieved a lower milking frequency compared to the previously described studies with 1.5 milkings/cow per day. Regardless of the cow to robot ratio implemented, the relatively low number of cows per AMS would result in a high initial investment for bigger scaled farms. These farms would be unlikely to capture any economic benefit of the investment (Rotz et al. 2003). However, it should also be noted that whilst dairy farms must operate profitably to remain sustainable, there are numerous factors that contribute to the decision making process; not all of which are based on economics.

To achieve optimal AMS efficiency a number of factors needs to be taken into consideration. Milking frequency, inter-milking interval, milk yield, teat cup attachment success rate, and length of the milking procedure are important functional efficiency aspects of the AMS (Gygax et al. 2007). The capacity of the system can not only be expressed as the number of milkings per day but needs to be considered in relation to the configurations of the AMS, number of milking stalls, the use of selection gates, milking frequency and herd size (Sonck and Donkers 1995). De Koning (2000) showed that reducing the milking interval would result in a lower yield per milking, with more milkings per day as a result. An increased milking interval on the other hand reduces the number of milkings per cow per day, creating the potential to milk more cows per unit and generally results in more milk harvested per unit each day. Because every milking contains a fixed 'handling' time (premilking teat preparation, attachment and post-milking tasks), a greater number of higher yielded milkings are desirable to minimise the proportion of handling time per day. An increase of 30 s per milking will result in a milking capacity reduction of 5 to 8% per day (de Koning and Ouweltjes 2000). A variable minimum milking interval was used in a study, based on individual cow production, stage of lactation and parity to minimise low yield milkings. The variable minimum milking interval resulted in an increased efficiency of the AMS unit (in kg produced per day) and a lower percentage of fetched cows as higher producing cows, > 30 kg, tended to arrive at the milking station only 30 to 60 min before the set 'standard' milking interval, resulting in this group being milked with a lower average milking interval (van Dooren et al. 2004a).

The time used for the different system operations, such as teat preparation, cup attachment, milking time of the cow and post-milking activities will influence the capacity of the AMS (Sonck and Donkers 1995; Jago et al. 2006a; Gygax et al. 2007; Davis et al. 2008a). The average percentage of successful milkings found in a study by Gygax (2007) was 95 to 98%, equating to 25 to 100 min of 'unproductive occupation time' per day, resulting in a reduction of the AMS capacity by at least 2 to 7% respectively. Two different studies have shown that the potential exists for time savings to be captured by not premilking and cleaning teats in an AMS (Jago et al. 2006a; Davis et al. 2008a), although the extrapolation of these results into the more complex RR system is yet to be proven. In AMS (individual boxes), the reduced crate time per milking was 32 and 66 s in the study of Jago et al. (2006a) and Davis et al. (2008) respectively. Reducing the preparation time of the cows and the number of failed milkings would increase the capacity of the AMS (Gygax et al. 2007). Whilst it is proven that the capacity of the AMS technology has increased markedly over recent years, investment cost in AMS on larger scaled farms will still be of concern limiting the adoption rate of the technology on these farms. This was also shown in a recent survey, with over 2600 dairy farms in the EU, in which no surveyed farms adopted AMS in herd sizes > 500 cows (Lassen et al. 2012). The RR, as the first high throughput AMS, is designed for larger scaled farms and is expected to result in lower per cow investment costs compared with the traditional AMS. However the actual capacity and the limitations of the RR, affecting the capacity, have never been studied before.

1.3.3 Teat cleaning

Different methods of premilking teat cleaning are used by different AMS manufacturers. In the European Union (EU) teat cleaning and preparation is a mandatory requirement[1]. Teat cleaning by wet horizontal rotating brushes, a separate teat-cup-like cleaning device and cleaning within the teat cup which is used for milking are all methods that have been integrated into AMS units. Knappstein et al. (2004) found significant cleaning efficiency differences between the different treatments for cleaning. However the farm hygiene and the initial contamination of the teats before milking were of even greater importance. In addition it was shown that teat cleaning significantly improved the teat cleanliness regardless of the technology.

It is known that premilking of the teats before milking releases oxytocin (OT) and induces milk ejection (Bruckmaier et al. 2001). Studies have been carried out to investigate the impact of AMS premilking teat preparation devices on OT release. It has been concluded that AMS results in sufficient stimulation to create the necessary milk ejection for a complete milk removal (Bruckmaier et al. 2001; Dzidic et al. 2004). Further investigation into the separate, teat-cup-like, cleaning device indicated no detectable difference in OT when either warm or cold water was used. Both methods were useful to induce milk ejection (Dzidic et al. 2004). Furthermore, a

[1] Commission directive 89/362/eec of 26 May 1989 on general conditions of hygiene in milk production holdings 1989: Official Journal L pp. 0030 - 0032.

delay of attachment after cleaning was not found to influence the milk let down process negatively (Macuhová et al. 2004).

Because premilking teat preparation is not commonly used in New Zealand and Australian pasture-based systems, AMS studies have been carried out in these countries to quantify the efficiency increase when no premilking teat preparation systems are used. As mentioned above, time savings of 32 and 66 s were realised without a significant negative impact on teat cup attachment success (Jago et al. 2006a) or milk yield (Davis et al. 2008a). However, neither study investigated the impact on milk hygiene in detail, nor did either study score the cleanliness or dirtiness of the teats. Although premilking teat preparation is not a mandatory requirement in Australia and New Zealand, and milking cows in an AMS without the use of teat cleaning did not affect the attachment success rates, the effects of premilking teat preparation in the RR are unknown. As the RR is a new technology it cannot be assumed that similar effects are to be found compared to the traditional AMS. Yet, no investigations have been published previously pertaining to effects of premilking teat preparation on attachment accuracy and milk harvesting in the RR.

1.3.4 Teat cup attachment

The success rate of attachment in an AMS is of crucial importance. While the system is operational without human intervention, it is important that the AMS will perform reliable teat cup attachments (Frost et al. 1993). It is commonly reported that failures in teat cup attachment will affect both the AMS capacity and milk production (Ipema and Stefanowska 2000; Bach and Busto 2005; Gygax et al. 2007). A study conducted across a ten-month period by Bach and Busto (2005), milking 83 cows twice daily, showed that 92.4% of total attachment attempts were successful, without taking cow behavioural aspects (e.g. kicking) into account in an AMS. Another study by Gygax et al. (2007) showed similar attachment results in groups of cows milked with two different AMS systems (2 groups per AMS brand), in which 20 cows were recorded on three successive days by means of video-recorded observations. In their study it was found that 94.5% and 97.5% where successful for the two different systems. An earlier study at the attachment success showed a success rate of 84% (Frost et al. 1993). The increase in success of teat cup attachment is an indication of the improvement in technical performance of AMS that has been achieved since early commercialisation of the technology. The improved performance may also be a result of the increased emphasis that is being put on maintenance and management of both AMS machines and the cows milked by them. High levels of successfully attachments are dependent on regular monitoring and management with timely maintenance programmes (e.g. addressing early warnings on attachment failures, singing udders–udder hair removal and managing poor conformation cows). Improvement of attachment success may have been created at least in part through having more 'suitable' cows, realised by ongoing genetic selection over the years, in the herd in combination with technical and management related improvements.

Alongside the improvements in attachment success the reduced speed of attachment has been reported by numerous authors. The early study conducted by Frost et al. (1993) showed an average attachment time of 2 min. More recent studies have reported performance improvements with attachment speeds ranging from 53 to 97 s for different systems (Dzidic et al. 2004; Luther et al. 2004; Christoph 2004; Macuhová et al. 2004).

It is known that milk accumulation rate (in the udder) is affected by the milking interval (Davis et al. 1998; Ouweltjes 1998). When a teat cup is not attached to the intended teat, the cow can leave the AMS unmilked in the quarter and the milking interval of the unmilked quarter will increase. A study conducted by Bach and Busto (2005) (average 7.6% unsuccessfully attached teats) showed that, when accounting for the effect of an extended milking interval (relative yield), milk production for the affected quarter was 26% lower than the quarters milked successfully at regular milkings. A study, investigating the effect of cows milked once or twice daily by diagonally opposed udder halves, showed a reduction of the milk yield for the once daily milked quarters of 28% (Stelwagen and Knight 1997). In contrast, there are studies reporting that no significant negative effects occur on milk yield due to incomplete milkings (Hamann et al. 2004). Ipema and Stefanowska (2000) concluded that the relative yield was lower after an unsuccessful milking event, but no effect was found on the total yield over a 24 h period. The impact of incomplete milkings is likely to vary depending on the production level and the absolute milking interval between successful milking sessions. Interestingly, it has also been reported that cows in an indoor system which had an unsuccessful milking (incomplete milking) tended to present themselves voluntarily to the AMS within a shorter inter-milking interval; 2 h after incomplete vs. 5 h after complete milking (Stefanowska et al. 1999a; Stefanowska et al. 1999b). Whilst the incomplete milking and the short subsequent milking interval of an incompletely milked cow may alleviate or minimise any production losses, AMS efficiency and potential capacity of the units will be reduced. In addition, incomplete milking events are more likely to be a bigger problem in future robotic systems in which one robotic arm serves several cows (e.g. the new RR). This is because in the RR for instance, the position of the udder in relation to the robotic arm is different (compared with AMS box) and also the space available for the cow to move is larger. However, neither the incidence of incomplete milkings in the RR nor the potential management solutions to minimise their impact, have been investigated yet.

1.4. Economic viability of automatic milking system

Investment costs for an AMS are generally higher compared to a conventional milking system (CMS). Studies have been carried out to investigate the economic impact of adopting an AMS. Most of the studies show the importance of labour reduction, an increase in milk production and/or a combination of both factors on profitability of AMS (Parsons 1988; Arendzen and van Schepping 2000; de Koning and Rodenburg 2004; Wade et al. 2004; Alford et al. 2010).

1.4.1 Labour

With the introduction of an AMS on a dairy farm, a change in labour requirement is expected. The physical milking task is carried out by the system but is replaced to some extent by management and monitoring tasks. Attention lists need to be checked and cows with alerts generated need to be followed-up (de Koning and Rodenburg 2004). Several studies have been conducted to investigate the effect of AMS introduction on labour requirements. A modelling study of Sonck (1995) showed a physical labour saving of 38%, however a questionnaire conducted with 107 North-West European farms showed an average labour saving of 20% (Mathijs 2004; Wouters and Mathijs 2004). The profitability on Dutch dairy farms was studied and showed a reduction of 29% in used labour, however, surprisingly the labour cost for payed employed labour was not reduced, suggesting that the benefits were being captured by the farm owner or business operator reducing their hours worked (Bijl et al. 2007). Consideration needs to be made for the large amount of variation that is inevitable between farms (de Koning and Rodenburg 2004). The results of any study would also depend on what the farmers are trying to achieve with the investment in an AMS. Different farmers capture the benefits in different ways, some of the examples in labour saving strategies are; reducing labour (employed and/or family employment), having the same number of labour units working less hours (not always resulting in a drop in cost but perhaps more sustainable with regard to labour retention) or even no changed labour input but having a higher proportion of time spend managing different aspects of the farm system, which could potentially result in an increase in farm profitability. The impacts of more futuristic automatic milk harvesting systems, like the RR, upon labour is currently unknown. This will likely be the subject of future studies as the AMS is increasingly adopted within different farm system types, for example in pasture-based systems (where impact on commercial farms is not well documented) and larger herds with RR technology.

1.4.2 Milk production

It is unlikely that AMS itself results in a direct and significant increase in milk production. Although indirect effects could result in a production increase if the factors limiting production are impacted. For example, if energy intake is the most limiting factor then an increase in production with AMS will only be achieved if higher energy intakes result with the AMS system. Similarly, if milking frequency is the most limiting factor then AMS may result in higher production levels if increased milking frequencies are realised (Utsumi 2011).

The effect of milking interval on milk production was investigated in several studies. It is shown that a decreased milking interval (increasing the milking frequency) will result in an increase in milk production (Erdman and Varner 1995; Hogeveen et al. 2000). Ouweltjes (1998) found a negative relation between an increase in milking interval on milk yield, expressed in grams per hour, with the greatest impact evident for the higher producing cows. The negative effect gradually declined as lactation progressed. The impact was also lower for heifers when compared with older cows. Numerous studies have shown a production increase resultant of milking cows three times compared with two times daily. Average production increases of 19% (Allen et al. 1986), 19 to 25% (Amos et al. 1985) and 17% (DePeters et al. 1985) have been reported when applying three milkings per day. However an analysis by Wade et al. (2004), with herd test data from 306 AMS farms, showed that the increase in milk production was only 2%, took into account a 'year effect' due to improved genetics resulting in an increased production level (12% increase is found without adjusting for the year effect). Therefore, expected increases in milk production resulting from increases in milking frequency should be budgeted for with caution as the impact will be dependent on a number of factors including genetic potential, initial production level, energy intake and physiological status of the herd.

Total cow's energy intake is significantly impacted by the farm system management, as demonstrated in a study by Utsumi (2011). It was shown that when cows were managed on pasture, with the availability of 1 kg concentrate per 4 kg milk in the AMS stall, the limiting factor in milk production was the energy intake level, rather than the milking frequency *per se*. This was compared with cows managed on pasture in combination with a PMR, or managed with a diet consisting of a TMR. Energy intake was not the limiting factor for cows managed with the TMR system, consequently a bigger effect on milk production was recorded for this system when the milking frequency was increased (Utsumi 2011).

1.4.3 Economic results

Questions have been raised and addressed around the economic consequences of introducing an AMS in several studies. However, the outcomes of each study varied considerably and were largely dependent on the assumptions made. In a simulation study of Dijkhuizen et al. (1997) a breakeven investment level per AMS unit of fl. 310,000 (€1 = 2.20 Dutch guilder; AU$210,000; exchange rate 5 yr AU$1 = €0.67) was found for a 125 cow herd, which was double than determined for a CMS. The break-even point in a Monte Carlo simulation analysis, in the United States was US$125,000 to 150,000 (AU$147,000–176,500; exchange rate 5 yr AU$1 = US$0.85) per AMS unit (Hyde and Engel 2002). The breakeven point in this study was higher than the actual investment cost, which indicated that system was economically viable under the assumptions presented in the study. Arendzen and Schepping (2000) used a room for investment (RFI) model to determine the maximum amount of money which could be invested in an AMS to realise the same net return when compared with an alternative CMS. In this study a RFI of €189,090 (AU$283,635) was determined in scenarios whereby a labour saving of 30% and a milk yield rise of 15% were realised. However, a dramatic reduction in the RFI of €66,000 (AU$99,000) was found when no labour savings or milk yield increase was anticipated, showing the importance of an increase in the production of the cows and a decrease in the labour employed on farm if a reduction in profitability is to be avoided. An analysis of commercial farm financial data of Dutch farms (n = 62 farms) showed no difference in gross margin between an AMS (n = 31) and a CMS (n = 31). In fact, the revenues, margins on dairy (revenues − cost of land use) and gross margins were significantly higher for AMS farms when data were analysed per full time employee (Bijl et al. 2007).

Wade et al. (2004) concluded that a difference in labour income of €16,500 (AU$24,750) was realised after introducing an AMS. Rotz et al. (2003) showed a loss in net return, depending on farm size, of US$0 to US$300/cow per year (AU$350). A simulated economical evaluation of AMS on New Zealand dairy farms, with 450 cows, indicated that the cost to produce one kg milk solid would cost 27% more when 5 AMS units were installed compared to a 40 bail rotary. This study suggested that with the New Zealand industry pricing, the capital cost of AMS equipment would need to decrease by 70%, or throughput capacity would need to be doubled to create the scenario whereby AMS would be as economically viable as CMS with a rotary milk harvesting unit (Jago et al. 2006b). Prior to any Australian AMS installations Armstrong et al. (1997) suggested that the investment cost of the AMS system needed to be below US$21,000 (AU$24,705) per unit to be comparable with a double-10 herringbone for a 500 cow herd and below US$17,000 (AU$20,000) to compete with a double 30 parallel in a 1500 cow herd.

The varied conclusions of AMS economic evaluations are created through the differences in assumptions used in the analyses and often without commercial farm financial data a conservative approach to the analysis is inevitable. Despite the negative outcomes of the evaluations conducted in New Zealand and Australia (Jago et al., 2006b and Armstrong et al., 1997, respectively) the fact is that farms in both countries have invested in AMS technology. This indicates either that the numbers and assumptions used were too conservative, costings have changed considerably, economic viability is achievable in different scenarios or that some farmers are willing to accept a reduction in economic performance of the farm system to capture non-financial benefits of AMS (e.g. lifestyle).

1.4.4 Economics of automatic milking systems in Australia

The Australian dairy sector and its operating systems are markedly different to those in European dairying counties where AMS is now well established. Analyses around the economical viability of AMS carried out in established AMS countries are less relevant for Australian dairy farmers. A recent examination carried out by Alford et al. (2010) looked at the feasibility of an AMS compared to a CMS with a high level of automation within Australia's pasture-based dairy industry. Data collected at the FutureDairy AMS farm (EMAI, Camden, NSW, Australia) was used in combination with ABARE and NSW Milkbiz benchmark data to model four different investment scenarios, including 160 cow, 240 cow, 320 cow and 400 cow herds in a pasture-based system. Four AMS scenarios, with 80 cows per unit, were compared with CMS, including an 18-cow swing over (160 cow herd), 24-cow swing over (240 cow herd), a 30-cow swing over or a 40-cow rotary (320 cow herd), and 50-cow rotary (400 cow herd).

In this conservative model it was assumed that no labour was saved with AMS in the 160 cow scenario, but with a 15%, 20% and 25% increased labour productivity in the 240, 320 and 400 cow herd scenarios respectively. A loss in milk production was estimated for the adaption phase at 10% for year one, and 5% in year two. No increases in milk production in subsequent years were factored into the model. All other costs were maintained constant across all farm sizes. In this investigation it was found that CMS achieved a higher net present value (NPV) and internal rate of return (IRR) for all the modelled scenarios compared to AMS. The difference in NPVs ranged from AU$174,730 (320 cows with a 30 unit swing over) to AU$83,817 (320 cows with a 40 bail rotary). The IRR was low for both CMS and AMS which ranged from 1.0% for the 160 cow herd to 5.6% for the 400 cow herd with CMS and from 0.3% for the 160 cow herd to 5.2% for the 400 cow AMS herd. The model also demonstrated an increased sensitivity of the larger scaled farm to milk price. Both CMS and AMS responded similarly when changes in milk price were calculated. It was found that with an increase of labour cost the AMS became more economically viable. A breakeven calculation indicated that labour cost should increase between 53 and 124% (depending on farm size) before a similar NPV is achieved with AMS. A reduction in capital investment of 37% was needed for the 160 cow herd and 13 to 30% for the other farm sizes, where labour savings were also assumed, before a breakeven NPV was achieved. It was clear within the boundaries of the (conservative) assumptions made that the capital investment in an AMS resulted in a lower economic return compared with a CMS however, it was also recognised that the analyses appeared to be conservative due to the lack of supporting commercial farm data available. An increase in labour productivity and a decreased adoption period production loss would have undoubtedly resulted in a reduced difference in NPV between the CMS and AMS scenarios. The authors of the report recognised that there were likely non-financial benefits that were not taken into account and even potential for increased profitability if more focus was place on farm system performance due to the reduced time spent milk harvesting. The question was raised; is investment in AMS simply an economical matter, or can social and business sustainability aspects can be valued and taken into account (Alford et al. 2010)? It was also recognised that investment in a new dairy (AMS or CMS) was a low returning capital investment but that sometimes the decision to install a new milk harvesting facility was essential to allow continued operation.

1.5. Incentive based voluntary milking

1.5.1 Concentrates

To achieve frequent visits of cows to the milking-unit in a voluntary system, concentrates are frequently used in AMS as an incentive to attract cows to the milking station (Bach et al. 2007; Halachmi et al. 2009; Madsen et al. 2010). Studies conducted as early as 1988 suggested that feeding in AMS was likely to be necessary to motivate cows to visit an AMS (Prescott et al. 1998b). This research (carried out with 12 cows volunteering around an AMS) showed that food was significantly more rewarding for a cow than the milking process itself. A more recent study of Melin et al. (2006) with 24 cows concluded that both milking and feeding acted as incentives for cows to present themselves to the AMS, however the motivation to get feed was stronger than the motivation to get milked.

The amount of concentrates offered in the AMS was studied by Halachmi et al. (2005). In this study, with 100 high yielding cows (43 kg milk/day) fed on a TMR plus concentrate offered at the AMS, the authors found that offering 1.2 kg/visit (3.9 kg consumed/day) did not result in a significant increase in the number of voluntary milkings compared to offering 7.0 kg/day (5.2 kg consumed/day). The small difference of 1.3 kg concentrates consumed per day between the groups did not result in an increase of voluntary milkings (3.2 milkings/cow.day for both groups), therefore it was concluded that 1.2 kg/visit was enough to attract cows to the AMS (Halachmi et al. 2005). A study of Bach et al. (2007) with lower producing cows (32 kg/day) showed a similar result to the study of Halachmi et al (2005). Offering a high concentrate allowance (maximum 8.0 kg; 6.8 kg consumed), or low allowance (maximum 3.0 kg; 2.6 kg consumed) did not lead to a significant difference in voluntary milkings or number of fetched cows. Furthermore, Migliorati et al. (2005) reported a similar finding with a herd average production of 27 kg milk/day, consuming 3.7 versus 1.4 kg/day. Interestingly a study carried out by Jago et at. (2007) with 27 grazing cows did not found a significant difference in milking frequency when cows were given 1.0 kg of crushed barley in the AMS unit compared to no incentive offered in the AMS unit. However a significant increase was found in the visiting frequency to the pre-selection unit (5.4 vs. 4.6 visits per day for the 1.0 kg vs. 0 kg treatments respectively) and milk production (23.6 vs. 22.5 kg milk/day) when the small volume of crushed barley was allocated.

The palatability of the available concentrates has been reported to have an effect on the attraction of the cows to the AMS (Migliorati et al. 2005; Madsen et al. 2010). Concentrates with sweetened flavour or additives were used as a ‘candy concept’ to attract cows to the AMS, but some authors warn that cows become accustomed to the taste which will decline the ‘novelty’ effect of certain feed types (Halachmi et al. 2006). Cows do however prefer concentrates containing a mixture of barley and oats compared to a standard fibre-rich concentrate composed off many ingredients, which resulted (in a study with 30 cows) in a significant increase in milking frequency from 2.96 to 3.31 milkings/cow per day (Madsen et al. 2010). In the same study, cows displayed a preference for wheat-based concentrates rather than concentrates based on maize or barley. However a different study by Rodenburg et al. 2004 concluded that small differences in the composition of concentrates did not influence the frequency of voluntary milkings nor the number of cows fetched. Conversely, mash and low strength concentrates were associated with a decreased number of milkings and an increase in the number of cows needing to be fetched for milking (Rodenburg et al. 2004). Studies conducted recently at the world’s first RR research facility showed that the provision of a small feed reward (upon entry to the system) created a marked impact on the cows willingness to volunteer onto the system. An increased waiting time of cows (Scott et al. 2011) and idle time of the system (Kolbach et al. 2011) was observed when no feed reward was provided on the RR.

1.5.2 Pasture-based system

European adoption rates and published literature indicate clear evidence that AMS is successfully integrated in indoor, incentive based, dairy systems. Research has been carried out to investigate the suitability of an AMS when grazed pasture is available periodically, with the focus on cow traffic between pasture and the dairy, milking frequencies and milk production (Salomonsson and Sporndly 2000; van Dooren et al. 2004a, b; Sporndly et al. 2004). It was concluded that AMS could be incorporated into a partial grazing system, but in general more labour is needed to fetch cows from the paddock to maintain a high milking frequency (2.1–2.8 milkings/cow per day). However these studies were conducted in Europe, where it is not common practice to graze cows throughout the year. During the summer cows were granted access to the paddocks for a period up to 20 h per day (range 5–20 h). Comparison between 12 and 24 h grazing in a study of Ketelaar-de Lauwere et al. (1999) reported a significant reduction in the milking frequency in the 24 h grazing treatment (2.3 milkings/cow per day) compared to other treatments (2.5–2.8 milkings/cow per day). A recent study conducted in the United States has shown similar results. When pasture was available for a longer period of the day (0–12 h/d) a reduction of the number of milkings (from 3.0 to 2.4 milkings/cow per day), milk yield (from 30.7 to 26.2 kg/cow per day) and an increased number of fetched cows was observed (Utsumi 2011). This shows that challenges are created when attempting to maintain a satisfactory milking frequency with as little as possible labour needed for fetching cows in a voluntary, distributed, pasture-based system.

The Greenfield project (Hamilton, New Zealand) and the FutureDairy project (Camden, NSW, Australia) investigated the feasibility of integrating AMS into a pasture-based milking system. The majority of Australian dairy farm systems are outdoor and pasture-based. In an outdoor pasture-based system, the cows are required to voluntarily move around the farm to be milked in the AMS. The most reliable motivation for this is to use food incentives for encouragement. In a pasture-based system this means that farmers need to place a sound effort on pasture management and allocation if they are to realise a high AMS utilisation rate and target milking frequencies. By giving the cows two fresh breaks of grass per day, the cows are forced to leave the paddocks to be milked at least once a day (Davis et al. 2007). Pasture allocation (size, timing and frequency of allocations) is the key factor affecting milking frequency and AMS utilisation in Australia. Jago et al. (2002) concluded that cows in a pasture-based voluntary system adapted rapidly with the use of incentives like, water placement, access to fresh pasture breaks and feed in the AMS box. Interestingly, Dickeson (2010) showed no negative short term effects of inaccurate pasture allocation, provided overall 48 h allocations of feed were reasonably accurate. Anecdotal evidence suggests that prolonged under or over allocation would likely impact significantly on milking frequency and milk production. Both the New Zealand Greenfield project (Davis et al. 2006) and Australian FutureDairy project (Davis et al. 2008b) have shown that it is possible to achieve adequate levels of pasture intake, pasture utilisation and maintain high quality pasture in a low-input, pasture-based system with an AMS.

1.6. Conclusions

AM systems are being widely adopted overseas in response to the high labour cost. Decreased labour input, more flexible use of labour and a potential increased production of cows (as a result of an increase in milking frequency) are additional key reasons for the high uptake of AMS. However Australia is predominately pasture-based, and uses a grazing system throughout the year to feed cows. This means that the dairy farming systems developed around AMS in Europe are not applicable to most Australian dairy farms. It has been concluded by the Greenfield project (Hamilton, New Zealand) and the FutureDairy project (Camden, NSW, Australia) that cows in a pasture-based voluntary AMS adapt very well with the use of food incentives for encouragement to visit the milking unit. Whilst there is a significant volume of published literature around many aspects of AMS operation the review of current literature did not expose any publications pertaining to the RR due to the infancy of the technology and very limited number of research installations. It was shown in this review that no data have been published around key factors of the RR, for instance the capacity, the effects of premilking teat preparation on attachment accuracy and the attachment success rates of the RR. Therefore this thesis will focus on the feasibility and operational efficiency of incorporating a novel RR into a pasture-based dairy farming system with voluntary cow traffic.

Chapter 2. First experiences with a high throughput automatic milking system: The robotic rotary (DeLaval AMR™)

Overview of Chapter 2

In Chapter 1 an overview of the Australian dairy industry was presented, indicating that pasture-based grazing systems are commonplace in Australia. It was also clear that the majority of published studies around automatic milking systems (AMS) were conducted in indoor systems, which means that the results are often not directly applicable to Australian dairy farms. In addition, all existing studies reported in the literature have been conducted with single- or multi-box AMS units. As there is currently no published work around the world's first high throughput AMS, the robotic rotary (RR), no benchmark is available for comparisons between the RR and existing published AMS data.

The aim of this Chapter is to introduce the RR in more detail and indentify key factors affecting its performance through rigorous statistical analyses. The system functions, performance and first-hand experiences are presented and an attempt is made to identify the key challenges arising from operating the system as the first farm in the world to operate the RR with voluntary and distributed cow traffic. This is the focus of Chapter 2.

First experiences with a high throughput automatic milking system: The robotic rotary (DeLaval AMR™)

2.1. Abstract

Key outputs of the functioning of the robotic rotary (RR, DeLaval AMR™, Tumba, Sweden) were summarised and factors contributing to the system performance and operational efficiency were statistical analysed and discussed. The RR is the world's first high throughput automatic milking system and is expected to be capable of milking 50 to 90 cows per hour (depending on the installation with either two or four robots). Data were collected from a selected period, between July 4 and September 5 2011, during which the RR was being managed as a 'commercial' operation with limited research related disruptions. It was found that time of the day significantly affected number of milkings and amount of milk harvested per hour with the lowest number of milkings occurring at 0400 h (5 cows milked and 55 kg milk harvested/h) and the highest at 1200 h (16 cows milked and 185 kg milk harvested/h). This highlighted the voluntary character of the system operational at the Elizabeth Macarthur Agricultural Institute site (Camden, NSW, Australia). This also indicated the need to explore management options that can potentially optimise RR performance, particularly in view of the incapability of the RR to flush individual units after each milking (meaning that time of the day with low visitation can result in too many units being shut down to avoid consequential high bacteria contamination of harvested milk). Attachment success rate was found to be significantly affected by the cows' parity, milking interval leading up to the recorded milking, and whether or not the milking was conducted after a previous incomplete milking. A significant difference in accuracy of attachment was found between individual quarters, with clear indication that the back quarters were more likely to be incompletely milked. It was shown that the right front teat had 2.2 times higher odds of being attached compared to the left back teat. The left front teat was attached 5.8 s significantly faster than the left back teat. Attachment times were also found to be affected by a significant interaction between milking interval and parity. In fact, cows with five or more lactations, with a milking interval between 12.7 and 18.7 h were fastest attached with an average attachment speed of 58 s. The slowest average attachment (72.5 s) was observed for heifers with a short milking interval (< 7.8 h). Milkings occurring after a previous incomplete milking were also slower to attach (1.2 s per milking) than first attempt milking sessions. The lower than desirable attachment success rate indicated that further studies are necessary to investigate the effect of different system installations, as the RR will have the option of installing and using a teat preparation module. As it was shown that the attachment success of cows

milked at a second attempt was affected by the milking interval leading up to the milking, different management strategies of incompletely milked cows could potentially lead to an increase of attachment success rate (at second attempt for milking). Based on the learnings presented this chapter, this thesis will focus on three key investigations; (1) coping mechanisms for periods of *underutilisation* of the RR to increase potential for harvesting high quality milk; (2) understanding the impact of premilking teat preparation on *attachment accuracy* to ensure farmers are well informed when deciding whether or not to install a teat preparation module*;* and (3) development of optimal *management strategies* of incomplete milked cows and associated implications for dairy layout.

2.2. Introduction

It has become evident that the throughput capacity and capital investment cost per cow of current automatic milking system (AMS) technology impinges on likely adoption of the technology enough for larger scaled farms with herds exceeding 500 cows. The high investment cost of AMS was already highlighted by Armstrong and Daugherty (1997) as one of the main factors limiting the adoption rate in the United States.

With the growing demand of labour and the increased interest in automation within the dairy industry a new technology has been developed. In September 2010, DeLaval (Tumba, Sweden) introduced the world's first robotic rotary (RR), the automatic milking rotary (AMR™; Rosengren 2010b). This is the first AMS developed for larger scaled dairy farms (Figure 2.1). The Australian national research program FutureDairy has been involved in the development of the RR, and a 16 bail prototype was installed and tested at the Elizabeth Macarthur Agricultural Institute site (Camden, NSW, Australia). The RR is expected to be capable of milking 50 up to 90 cows per hour (depending on the installation with either two or four robots and system management).

This new piece of technology is expected to provide an alternative to the existing solutions in the automation of the dairy industry and will help to address challenges on bigger scaled farms related to availability of, suitable, employed labour in the near future.

2.3. The robotic rotary

2.3.1 The milking stall

The commercially available AMS units are commonly defined as being either single- or multi-box systems. The single-box system is comprised of integrated milking equipment and one robotic device which remains with and is solely dedicated to a single milking stall. The multi-box systems, of up to five stalls, 'share' a mobile robotic device or 'robotic arm', which cleans teats and attaches teat cups to cows in a number of milking stalls. All systems (single- and multi-box) are equipped with electronic ID readers to indentify whether or not a cow has milking permission, dispense an individually based portion of concentrate while the cow is being milked and allow electronic data pertaining to each cow visit to be recorded by the system software.

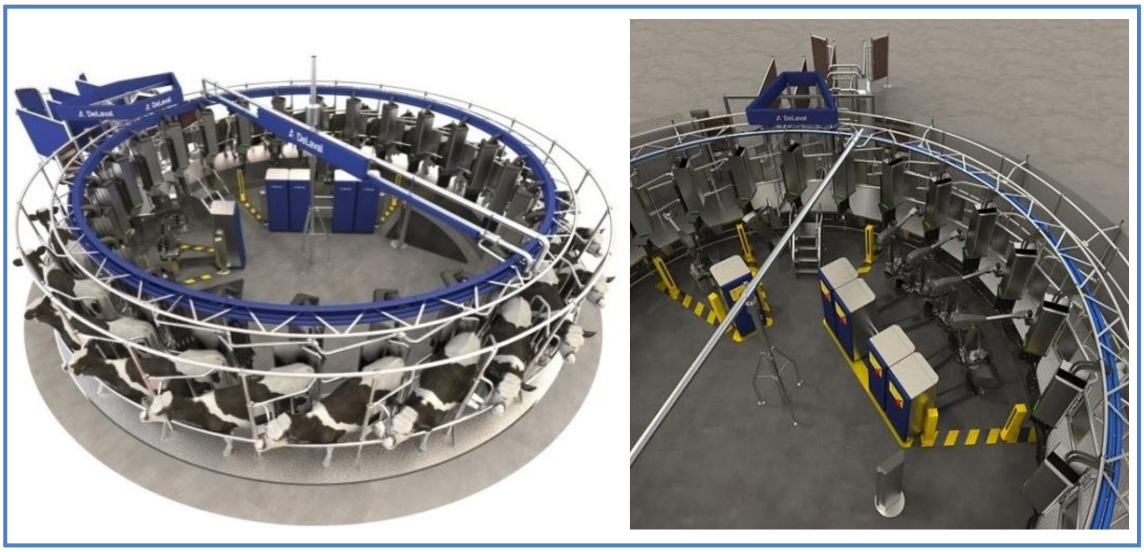

Figure 2.1: DeLaval automatic milking rotary (Tumba, Sweden), world's first robotic rotary dairy (Rosengren 2010b)

The RR on the other hand is of a completely different design compared to any of the existing AMS technologies. The configuration is essentially a **herringbone rotary** (DeLaval HBR™, Tumba, Sweden). The prototype RR used in this study contained **16 bails** (Figure 2.2), however it should be noted that the commercial versions will have a total of 24 bails on the rotary platform. In the prototype RR the cows are standing with an angle of 120° in relation to the robotic devices (their position is 30° in relation to the actual rotary platform). With single- or multi-box systems, the angle of the cows' position with the robotic devices is 90°, and the robot generally accesses the udder by approaching from the side between the front and back legs. However in September 2011, the first commercial AMS which approaches the udder between the back legs of the cow to attach teat cups (180°) was launched (Boumatic Robotics 2011).

The robotic devices in the RR remain stationary whilst the rotary platform rotates the cow around from the entry point to the exit point in a stop-start operation. With the installation of multiple robotic devices, up to four cows can be simultaneously cleaned and attached. This reduces the robot 'attention' time per cow associated with cleaning and attaching. The fact that the robotic arm does not remain with the cow during the entire milking process (as it does with the single- and multi-box systems) means the arm can spend a far greater proportion of time attending to cleaning or attaching cups to cows thereby creating a much higher throughput compared to traditional single- or multi-box AMS.

The RR undergoes a defined process necessary for milking the cow before releasing her back to the herd. For the purpose of clarity to the reader we will refer (in this section) to bail position numbers as shown in Figure 2.2 even though it should be remembered that the actual bail will progressively move from position 16 in an anticlockwise rotation. The operation cycle in the 16 bail prototype RR with two robots is as follows: (1) a cow presents herself at the *entry* (position 16) and is electronically 'recognised' by the transponder she carries around her neck; (2) if position 16 (termed "buffer zone" in Figure 2.2) is already occupied the cow waiting at the gate will not gain access until the next bail becomes available at position 16 (i.e. the platform rotates one position); the platform will not rotate until the robots have completed their action and are in a "parked" position. Cows receive their first ~150 g portion of pelleted concentrate whilst in the buffer zone position; (3) when robot actions are complete, the cow is rotated towards the first robot, bail position 15 (the TPM zone in Figure 2.2), where teats are cleaned, foremilk is removed and the milk let down is stimulated with a teat-cup-like cleaning device whilst a second portion of ~150 g feed is dispensed, meanwhile the next cow gains access to bail position 16 in the buffer zone; (4) at the same time, teat cups are being attached to the cow positioned at the ACA zone (bail position 14 in Figure 2.2); (5) when both robots, the TPM and ACA have completed their actions and are parked, and a cow has entered the platform in bail position 16 (buffer zone), a rotation step ($1/16^{th}$ of a rotation) will take the 'prepared' cow to the ACA position (show as bail position 14 in Figure 2.2); (6) at the ACA zone teat-cups are collected from a "magazine" two at a time and are attached individually (every teat has a separate in-line milk meter that monitors milk volume (flow) and milk quality (conductivity); (7) the cow is progressively rotated towards the exit of the RR platform in a step-wise fashion at which point she is expected to voluntarily walk off the platform. Meanwhile subsequent cows enter the platform and go through the same premilking teat preparation and cup attachment process described above. When a cow is still being milked as she enters the "safe zone" (shown as the grey bar at bail position 4 in Figure 2.2) any further platform rotations are prevented and all other actions are paused until the milking of that cow is complete. When no cows enter an available bail in the buffer zone, the system waits for up to 90 s (settable time) after all robot functions are complete and the cow in the safe zone is finished milking before a "step-time-out" (STO) occurs. If a STO occurs the result will be that the available bail will remain unutilised and the platform rotates to the next bail. The STO function ensures that cows standing on the platform will continue to be rotated so that they can exit the platform even when no (or few) cows are entering the platform.

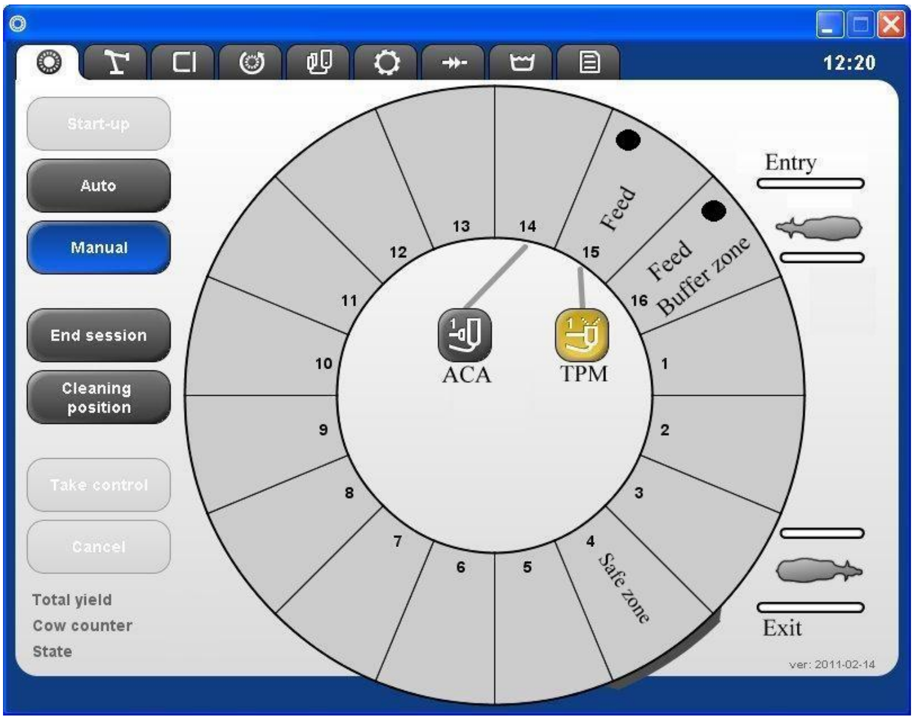

Figure 2.2: Schematic of the RR showing; the entry to the rotary, the buffer bail zone, teat preparation module (TPM; in yellow), automatic cup attacher (ACA; in grey), the safe zone (bail 4), exit from the rotary platform and the feed available at the TPM and buffer bail positions (bails 15 and 16, two separate feed bins are positioned as indicated by the black circles; schematic graphic user interface of AMR™; courtesy of DeLaval)

The three key functionality differences between the AMS and RR are: (1) An AMS unit can conduct fully automated equipment washing and in particular can rinse milk residue from the equipment after settable "idle" periods but the RR has no automated washing or rinsing functionality; (2) unlike a single- or multi-box AMS the RR cannot automatically divert milk from any individual cow to a separate destination (e.g. put antibiotic milk to the drain or colostrums to a different tank) and (3) conventional AMS have the ability to provide controlled volumes of concentrates to cows during the milk harvesting session, whereas the RR has no integrated feeding functions. Whilst these three functionalities may, or may not, be incorporated into the RR as the technology is further developed, it has been recognised that at least the first commercial versions of the equipment will not have these three functions (R. Mulder, DeLaval, pers. comm.).

To cope with the lack of automated system washing, staff put through a full system wash at least twice a day. The lack of automated rinses after idle periods creates a greater challenge. Any individual bail that remains idle for a settable period of time can be automatically deactivated and is only reactivated after the next full system wash is completed. During periods of low utilisation more and more bails become deactivated as the time since washing progresses and the potential exists to have end up with only a small number of bails active during periods of low cow traffic. The user can choose to start the system with only a proportion of bails active after a wash and can activate 'clean' bails progressively as required thereby increasing the potential to keep a critical number of bails active at all times. Clearly the impact of different starting sequences on animal and whole RR efficiency requires further investigation.

The lack of a milk diversion function makes it necessary to have the 'abnormal milk' cows managed as a separate group and bought to the dairy twice daily for milking–this is best timed to be conducted prior to initiation of the system wash.

Whilst the prototype RR does not have an integrated 'in-bail' feeding system, installation of feed stations in a post-milking area allows cows to be fed individual allocations of pelleted concentrate. The prototype also has two fixed feeding bins that are set to dispense ~150 g concentrates (per bin), as cows enter the buffer bail and during premilking teat preparation (bail positions 15 and 16 in Figure 2.2). Yet, the importance of the small feed reward in the overall functioning and operational efficiency of the RR system needs to be quantified.

2.3.2 Robotic devices

To suit the demand of different farm sizes, the RR can be equipped with a varied number of robotic devices. Depending on the required throughput capacity, the RR can have two, (one teat cleaning module–TPM and an automatic cup attacher–ACA), three (one TPM, one ACA and a teat spray module–TSM), or five robotic devices (two TMPs, two ACAs and one TSM). The robotic devices essentially imitate a milker by way of an 'arm' that cleans teats, and picks up and attaches cups. The arm is fixed to the floor inside the RR platform and whilst the arm has vertical, lateral and horizontal planes of movement the footing remains stationary (Figure 2.3). The cows are rotated in steps towards each robotic device. When two robots are implemented (one TPM and one ACA), the TPM cleans all four teats and the ACA attaches all four teat cups to the udder. It is anticipated that the system with two robots is able to milk up to 50 cows per hour. Conversely, if four robotic devices are installed, up to 90 cows per hour can be milked, the TPMs and ACAs attend two teats each per rotation, reducing the 'attention time' between each robot and cow and increasing the system throughput capacity. The various configurations of robots in a commercial installation will be largely determined by targeted throughput potential and whether or not the operation will be managed with batch milking (cows bought to the dairy in batches) or voluntary cow traffic (relatively constant flow of cows bringing themselves to the dairy throughout the day and night).

Whilst every teat of every cow in the herd will be given a co-ordinate (automatically updated), the position of the teats is refined by the robots with laser and camera technology at each milking session. To locate the cow's position within the designated bail, time-of-flight (ToF) cameras are used with a translation created between the cow position, the cows' fixed point, and the position of the udder. The ToF camera system calculates the distance and position to the cow based on the known speed of light, measuring the time-of-flight of a light signal between the camera and the cow for each point of the image.

Figure 2.3: Robotic devices; installation of two teat preparation modules (TPM, in foreground) with fixed cleaning cups (circled) and two automatic cup attachers (ACA, in the background; www.DeLaval.com)

2.3.3 Teat cleaning

Users of the RR will have the *option* of purchasing and installing a TPM. The purchase and installation of one or more TPM(s) will not be compulsory and farmers may opt to reduce the cost of the capital infrastructure by choosing not to install a TPM. The TPM carries a fixed 'teat-cup-like' cleaning cup. Teats are cleaned and stimulated while water circulates gently with air through the cup, the teats gets dried at the end of the circulation by activating vacuum in the cleaning device (Figure 2.4). The cleaning process also strips the foremilk from each teat, this foremilk is stored in a separate receiver and is later diverted to the drain. The cleaning system operates on a separate circuit from the milking lines, preventing foremilk from contaminating the milk transported to the vat. The intensity of the cleaning process is settable in DelPro (DeLaval AMS management support software) depending on the general dirtiness of the teats. Four programs can be chosen (extra light, light, medium and heavy), in which the individual teat contact time ranges from 5.5 s to 13 s. Temperature of the premilking teat preparation water is settable but was maintained at 18 C° in all the studies presented in this thesis. Despite the TPM being an optional function in the commercial RR, its importance and impact for pasture-based systems and RR functioning deserves to be elucidated.

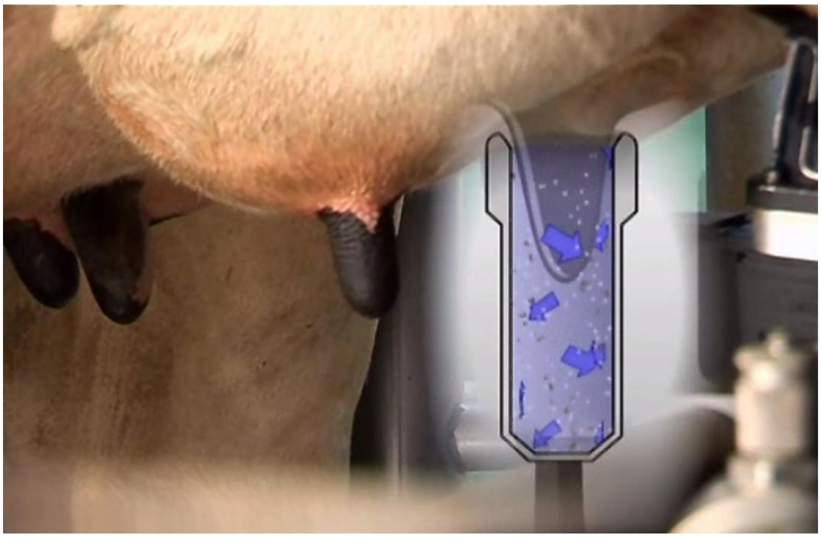

Figure 2.4: Teat cleaning device, the teat preparation module (TPM; www.DeLaval.com)

2.3.4 Cup attachment

Up to two ACAs can be installed in the first commercial versions of the RR. The ACA collects cups from a magazine for attachment, a similar technique as used by the DeLaval VMS™ (voluntary milking system). The ACA is equipped with a double magnetic gripper which is able to collect two teat cups at a time (Figure 2.5). This reduces 'unnecessary' handling time associated with collecting cups from a magazine, one at a time, thereby increasing the systems' capacity. The four teats cups are attached in succession starting with the back teats, closest to the robotic device, and finishing with the front teat, furthest away from the robot. The back teats are attached first as the back quarters generally have the largest volume of milk, and take the longest to finish milking. It also makes sense to attach the back cups prior to the front cups to minimise the need for the arm to weave amongst cups that have already been attached.

Figure 2.5: Teat cup attachment robot, the automatic cup attacher (ACA) locating back teats for attachment of cups prior to retrieving the front cups from the magazine (out of view). The red laser line can be seen on the right back teat (this picture is particular to a clockwise, 24-bail RR; www.DeLaval.com)

2.3.5 Teat disinfection

The installation of a TSM is optional in the commercial versions of the RR. The TSM is equipped with an integrated nozzle which sprays a post-milking disinfectant on the teats upon completion of the milk harvesting session (Figure 2.6). The teats are individually located by a ToF camera and are sprayed when the cow is rotated to the TSM bail position. The prototype, 16-bail, RR used in this study does not have a TSM installed due to the fact that this robotic device could not be retrofitted into the prototype RR. Instead a WETiT®, 'walk-over', teat sprayer was installed, disinfecting teats after the cows leave the platform (in an exit lane). Commercial installations will have the option of integrating a TSM or another brand of walk-over disinfecting device. However it should be noted that the walk-over type teat sprayers are not linked into the system and will be unlikely to have the targeted accuracy of the TSM–nor will there be any system alarm functions to alert the farmer to any technical issues requiring attention.

Figure 2.6: Post-milking disinfection of teats, the teat spray module (TSM; www.DeLaval.com)

2.3.6 Control system and sensors

To control the milking process and monitor the milk quality, sensors are used to replace the 'controlling and monitoring work of a human operator'. The sensors essentially replace the observational sense of a human and their task is to monitor the technical functioning of the RR, e.g. cow identification, vacuum level monitoring, cow position sensing, teat cup attachment, start of the milk letdown process and monitoring of the milk harvesting process and milk properties. The sensors provide the system with the information required to generate the necessary reporting, alerts and alarms that then allow the system to be operated without direct human involvement.

Sensors are used to detect the position of the cow on the RR platform. In comparison to the single- and multi-box AMS, the RR has many more rotating and moving parts. To ensure the welfare of the cow is maintained and to prevent a poorly positioned cow becoming wedged, sensors monitor her position. Strategically positioned 'squeeze' sensors at the entry, exit and platform drivers will be activated when a cow does not position herself correctly/safely or if a cow does not exit the platform within the expected time. An alarm is sent out to the farmer when any of these sensors is activated for a short period of time (time is non-settable and is specific to the sensor location).

Sensor technology is used to monitor the milk quality and detect abnormalities. The RR operates with quarter milking functions; similarly to a single- or multi-box AMS unit. Every quarter is milked separately, and the milk harvested from each quarter is measured by an in-line milk meter (DeLaval MM27BC). Each milk meter measures milk yield, milk flow rates, blood presence and conductivity levels of the milk. All quarter-milk-data (of every milking session) is stored in a database, which is accessed though the DelPro management software program. Reports and monitoring applications are used to alert the farmer to abnormalities at quarter-, cow-, herd- and machine levels.

2.4. Materials and methods

Throughout 2009 and 2010 the prototype RR was installed, tested and co-developed. As the first (and currently only in the world) RR farm to operate with voluntary cow traffic, the remainder of this section is dedicated to summarise key data that was collected during operation with voluntary traffic. The data presented here help to demonstrate the throughput, accuracy and operation of the prototype RR within the farm system management synonymous with distributed milking.

2.4.1 Data collection period

Milking and system performance data were collected and analysed for the period between July 4 and September 5 2011. In total 18,500 milking sessions were carried out over a 63 day period with a mixed breed herd containing on average 170 cows (range 163–178 cows on any one day; majority Holstein-Frisian and approximately 10-15% Illawarra). In the collecting period the RR was being managed as a 'commercial' operation with limited disruptions that might otherwise be created by component research. Average milk production level was 21.5 kg/cow per day (median 20.3 kg; SD 7.0 kg), with 11.4 kg/milking (median 11.0 kg, SD 6.2 kg) and an average milking frequency of 1.93 milkings/cow per day (median 1.86; SD 0.57; including repeated milkings of incomplete cows). Cows incompletely milked at the first milking gained access to the

RR for a second attempt by being sent back to the holding yard when passing a set of automatic drafting gates (smart selection gates; SSG, DeLaval, Tumba, Sweden). However a milking incomplete for the second consecutive time would result in a cow being sent back to the paddock without having access to the RR for a third attempt at milking. The milking herd was representative of a typical year-round calving herd with average 166 days in milk (median 148 d; SD 106 d) and an average parity of 2.9 lactations (range 1–10; median 3; SD 1.8). Cows were managed and grazed as per recommended practice (Kerrisk 2010), as a single voluntarily trafficking herd.

The RR was operated with full voluntary cow traffic (and the associated distributed milkings) from early February 2011. As a result all cows milked during the data collection period had gained previous experience with the system before commencement of the study. Cows were granted access to an allocation of pasture each day from 0900 to 1800 h and another fresh allocation of pasture each night from 1800 to 0900 h. Total feed allocation target was ~21 kg DM/cow per day, which was comprised of 2.6 kg concentrates as consumed through automatic concentrate feeders, an additional small allocation of pelleted concentrate in the first two bails of the RR to encourage voluntary cow traffic (~0.3 kg/visit) and the remainder of the diet as pasture.

2.4.2 Statistical analyses

2.4.2.1 Output variable

Analyses were conducted to determine: (1) whether or not the distribution of the number of milkings per hour, and the total amount of harvested milk, were affected by the hour/period of the day. Next the data were analysed to determine any trends in system performance by explanatory variables. Impacts were measured on: (2) probability of a successful milking; (3) probability of whether a cow incomplete at the first milking was subsequently completely milked at the second attempt; (4) probability of a successful attachment of individual quarters (left back = LB; right back = RB; left front = LF; and right front = RF); and (5) the effect of explanatory variables on attachment speed.

Data generated were collected electronically and exported from the VMSClient management program and a custom made program (DeLaval, Tumba, Sweden), which logged all the robotic actions times. These robotic action times were used to accurately calculate the cleaning and attachment times of the TPM and the ACA. The exported data also included unsuccessful milkings recorded by the system, including all instances whereby any individual quarter did not have a teat cup attached during the milking session. To investigate the effect of a successful (all four quarters milked) milking on the attachment success at the subsequent milking, all the incomplete milkings were classified as follows: A milking with a successful milking prior to the observed session was classified as the first attempt, when the milking is subsequent to a previous incomplete milking the milking was classified as a second attempt.

For the analysis of the system utilisation (by hour) throughout the day, all data were summarised per hour across the collection period. This dataset was used to analyse the number of milkings distributed across a 24 h period. In addition the amount of milk harvested across the day was investigated. To analyse the attachment success of the ACA, data were filtered to remove milkings (3,200 milkings removed) that involved human intervention (predominantly those conducted with cows in the abnormal milk group which were manually milked twice per day).

2.4.2.2 Explanatory variables

Electronically collected data through VMSClient included; milking interval (MI; time between milkings in hours), average daily milk production level (7 day average production; kg), stage of lactation (days in milk; DIM), parity (lactation number) and the milk point (MP) the cow entered for each milking session (1 out of 16 available positions on the rotary).

2.4.2.3 Statistical models

The data were analysed with GenStat 13th Edition (VSN International, Hertfordshire, UK). Linear mixed models (fitted using a REML procedure) were used to test the association of explanatory variables with the numerical outcome variables: the distribution of the number of milkings and the amount of milk harvested (outcome 1 described above), and the effect on attachment speed (as outcome 5 described above). Week of observation was used as a random effect in the first model (the distribution of the number of milkings and the amount of milk harvested). Week of observation, animal, and their interaction, MP, and MP $\times$ week interactions were used as random effects in the fourth model (effects on attachment speed). Model assumptions of normality and equal variance were evaluated, and if invalid, outcomes were transformed to meet the assumptions. Attachment speed data were log-transformed as it was unable to meet the assumption of normality.

Generalised linear mixed models (GLMM) were used for binary data to test association of the electronically collected explanatory variables with the outcome variables: probability of a successful milking (outcome variable 2), and probability of successful second attempt (outcome variable 3). For this third outcome all successful milkings prior to the observed milking were excluded for this analysis and the MI was regrouped in quartiles. Similar random effects were used as described before (week + animal + animal × week + MP + MP × week). To test the association of individual teats (LB, RB, LF and RF) on the probability of a successful attached milking, univariable GLMM were used with animal as random effect.

Linearity for the explanatory variables with the outcome variable was tested using restricted cubic splines. The variables were categorised in quartiles and used for further analyses as they were not able to meet the assumption of linearity. All variables with a P-value < 0.25 in univariable analyses were included in the multivariable models. Insignificant variables (P-values > 0.05) were then eliminated using a backward stepwise approach. In addition all their first order interactions were included as fixed effects and were retained when significant. Odds ratios and their confidence limits from the final binary model, and predicted means of the linear mixed models are presented and discussed.

2.5. Results

2.5.1 Descriptive results

In total 15,300 milkings were conducted by the ACA (attachment time averaged 69.4 s, median 60.0 s, SD 31.0 s) and 13,305 milkings received a teat cleaning by the TPM (average cleaning time 70.3 s, median 69.0 s, SD 11.9 s).

2.5.2 System utilisation across the day

The maximum number of voluntary milkings per hour was 33, with 455 kg milk harvested per hour. Being a voluntary system, cow traffic has the potential to be the primary limiting factor of throughput capacity across a 24-hour period (i.e. the RR cannot milk more cows if cows do not present themselves on the platform). It can be seen (Figure 2.7) that the number of milkings at night decreased (particularly between 0300–0500 h). The back transformed predicted means and predicted means of the amount of harvested milk are shown in Figure 2.7. Significant differences between hours of the day were observed. The low throughput periods observed around 0500 to 0700 h and again at 1700 to 1800 h were associated with reduced throughput created by manual initiation of the system washes.

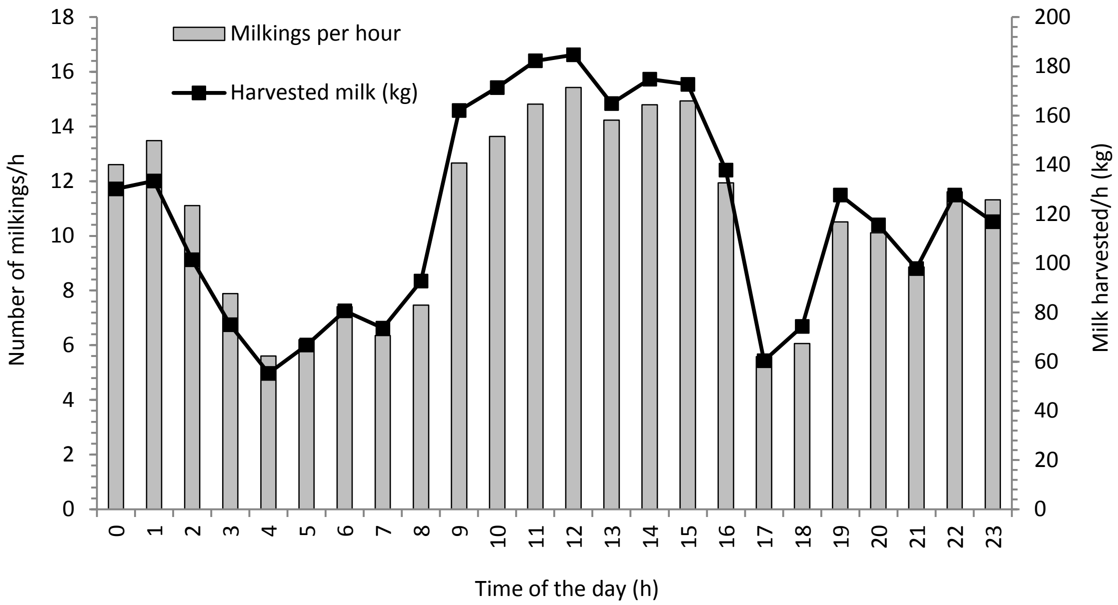

Figure 2.7: Back transformed predicted means of the distribution of the number of milkings and litres harvested per hour of the day. Week was included as a random effect in the model

2.5.3 Attachment success

Figure 2.8 shows the percentage of incomplete milkings for the first and second attempts. Results of the univariable analysis for the success rate of all attachments are shown in Table 2.1 and the final model is shown in Table 2.2. This model shows that a significant effect was found on the attachment success rate by parity, milking interval and whether or not the observed milking was a second attempt on milking. Heifers were the least likely to be successfully attached, with cows in the fifth parity being the most likely of having a successful attachment. Cows with a milking interval < 7.8 h had the highest chance of having a failed milking (Table 2.2).

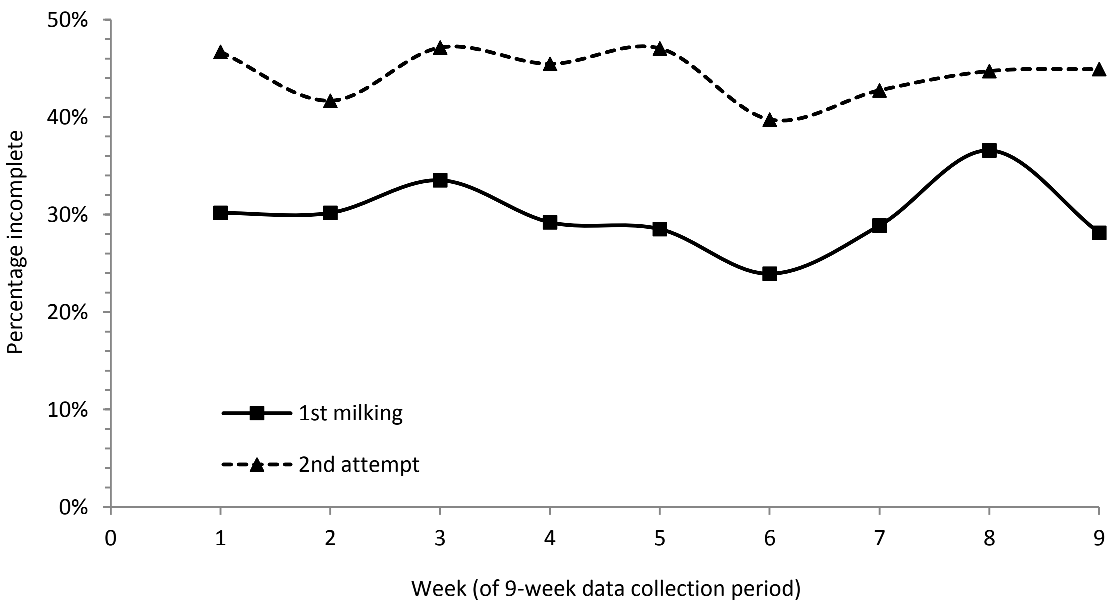

Figure 2.8: Percentage of incomplete milkings at 1st attempt and 2nd attempt

Table 2.1: Univariable results to investigate the association of explanatory variables on probability of a successful attachment. Week, animal, week × animal, milking point and milking point × week interactions were included as random effects

Effect	Categories	Estimate	Standard Error	Odds (95% CI^)	P-value
Days in milk					0.495
	<83	0.00			
	84–148	-0.13	0.10	0.88 (0.72, 1.07)	
	149–248	-0.11	0.10	0.89 (0.73, 1.09)	
	>248	-0.13	0.10	0.88 (0.72, 1.07)	
Parity					<0.001
	1	0.00			
	2	0.16	0.14	1.17 (0.89, 1.54)	
	3+4	0.29	0.14	1.34 (1.02, 1.76)	
	≥5	0.59	0.14	1.80 (1.37, 2.37)	
Milking interval					<0.001
	<7.8	0.00			
	7.8–12.7	0.60	0.05	1.83 (1.65, 2.03)	
	12.7–18.7	0.73	0.05	2.08 (1.87, 2.31)	
	>18.7	0.62	0.05	1.87 (1.68, 2.07)	
Production 7 d average					0.653
	<16.7	0.00			
	16.7–20.3	0.03	0.08	1.03 (0.89, 1.20)	
	20.4–25.2	0.05	0.08	1.05 (0.90, 1.22)	
	>25.2	0.12	0.08	1.12 (0.97, 1.31)	
2nd attempt at milking					<0.001
	Yes	0.00			
	No	0.32	0.04	1.38 (1.28, 1.49)	

^Confidence interval

Table 2.2: Final generalised linear mixed model to investigate the association of explanatory variables with the outcome variable–probability of a successful attachment. Week, animal, week × animal, milking point and milking point × week interactions were included as random effects

Effect	Categories	Estimate	Standard Error	Odds (95% CI^)	P-value
Intercept		0.07	0.11		
Parity					<0.001
	1	0.00			
	2	0.14	0.13	1.15 (0.88, 1.50)	
	3+4	0.29	0.13	1.33 (1.02, 1.73)	
	≥5	0.58	0.13	1.78 (1.37, 2.31)	
Milking interval					
	<7.8	0.00			<0.001
	7.8–12.7	0.57	0.05	1.77 (1.59, 1.97)	
	12.7–18.7	0.69	0.05	1.99 (1.79, 2.22)	
	>18.7	0.58	0.05	1.78 (1.60, 1.98)	
2nd attempt at milking					0.002
	Yes	0.00			
	No	0.13	0.04	1.14 (1.05, 1.23)	

^Confidence interval

The final model for the outcome variable, probability of a successful attachment attempt, after backwards stepwise elimination, is shown in Table 2.3. It was found that cows with a MI ≤ 2.5 h had a decreased likelihood of success, as they had a 3 times lower odds of a successful attachment.

Table 2.3: Final generalised linear mixed model to investigate the association of explanatory variables with the outcome variable–probability of a successful second attachment attempt (after a previous incomplete milking). Week, animal, week × animal, milking point and milking point × week interactions were included as random effects

Effect	Categories	Estimate	Standard Error	Odds (95% CI^)	P-value
Intercept		-0.49	0.08		
Milking interval					<0.001
	≤2.5	0.00			
	2.6–9.2	1.11	0.09	3.02 (2.54, 3.59)	
	9.2–15.8	1.10	0.09	3.01 (2.53, 3.57)	
	≥15.8	1.06	0.09	2.89 (2.43, 3.44)	

^Confidence interval

2.5.4 Incidence of quarter specific incompletes

The incomplete milkings were further investigated and are reported here at the quarter level. Figure 2.9 shows the distribution of incomplete quarters across the data collection period. It is evident that the proportion of left back (LB) incompletes (and the right back to a lesser extent; RB) was consistently high compared with the left front (LF) and right front (RF) quarters.

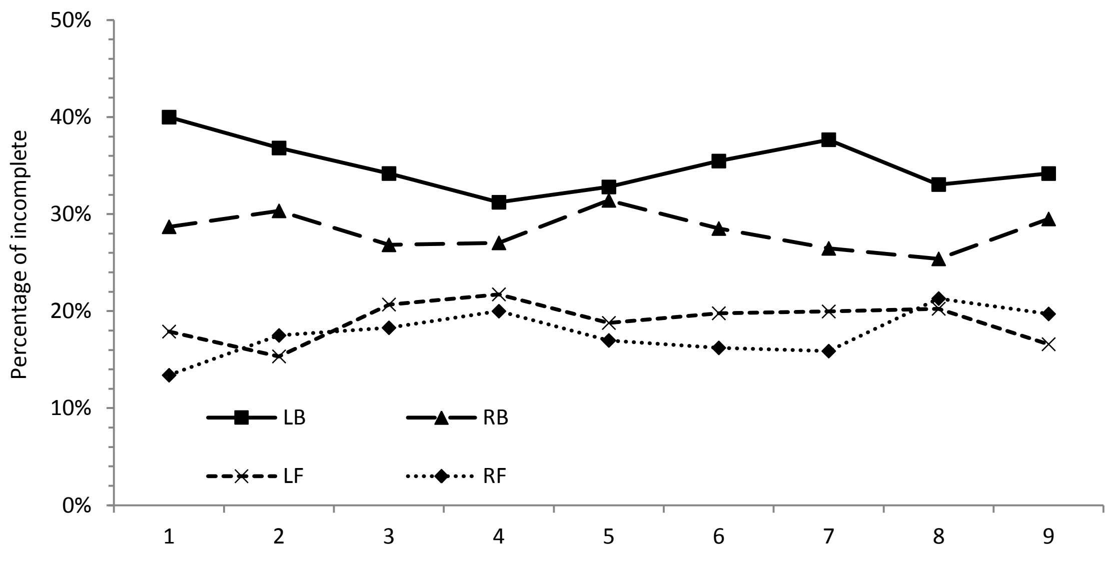

Figure 2.9: Distribution of incomplete quarters of all attempts across the 9 week period (LB = left back, RB = right back, LF = left front and RF = right front)

The effect, at univariable level, of individual quarters on attachment failure is shown in Table 2.4. Attachment failure with a LB quarter had a 2.2 times higher odds compared to the RF quarter. The back transformed means of the GLMM analysis showed that 16.5% of the milkings resulted in a milking with an incomplete LB-, 13.2% with RB-, 8.8% with LF- and 8.2% with a RF quarter.

Table 2.4: Effects of individual quarters on attachment success and attachment time, animal was included as a random effect in the models

Effect	TEAT			
	LB	RB	LF	RF
Attachment success	2.22 (2.07, 2.38)[a]	1.71 (1.59, 1.83)[b]	1.08 (1.01, 1.16)[c]	1.00*[d]
Attachment time	13.4 ± 0.11[a]	10.5 ± 0.13[b]	7.6 ± 0.08[d]	8.7 ± 0.09[c]

[a,b,c,d] Means within row without common lowercase superscript letter are significantly different (P < 0.05)
Values shown for attachment success as odds ratio (95% confidence interval between brackets); attachment times as back transformed predicted means ± S.E.M
LB = left back; RB = right back; LF = left front; RF = right front

2.5.5 Robotic operation times

The average attachment time was 60 s across the 9-week data collection period. The final REML model is shown in Table 2.5. There was a significant interaction between MI and cows' parity. The interacting back transformed predicted means of these two variables are shown in Table 2.6. Further investigation into the differences between quarters showed that the LB followed by the RB quarter were attached slowest (Table 2.4). Attachment times per quarter shown do not include times associated with collection of teat cups from the magazine before attachment commenced.

Table 2.5: Final Linear mixed model to investigate the association of explanatory variables with the outcome variable–attachment time per milking. Week, animal and their interaction, milking point and milking point × week interactions were included as random effects

Effect	Categories	Estimate	Standard Error	95% CI^		P-value
				Lower	Upper	
Intercept		4.27	0.04			
2nd attempt at milking						0.01
	Yes	0				
	No	0.02	0.007	0.01	0.03	
Parity						0.031
	1	0				
	2	-0.08	0.04	-0.16	0.00	
	3+4	-0.09	0.04	-0.17	-0.20	
	≥5	-0.20	0.04	-0.27	-0.12	
Milking interval						<0.001
	<7.8	0				
	7.8–12.7	-0.07	0.01	-0.10	-0.04	
	12.7–18.7	-0.09	0.01	-0.12	-0.06	
	>18.7	-0.08	0.01	-0.11	-0.05	
MI × parity						<0.001
	12.7–18.7 × ≥5	0.07	0.03	0.02	0.11	

^Confidence interval

Table 2.6: Interaction terms between parity and milking interval on attachment time (shown as back transformed predicted means; sec)

Parity	Milking interval (h)			
	<7.8	7.8–12.7	12.7–18.7	>18.7
1	72.5^{Cb}	67.8^{Cab}	65.9^{Ca}	66.8^{BCa}
2	66.9^{B}	63.1^{B}	61.9^{B}	63.2^{A}
3 + 4	65.9^{B}	61.1^{BC}	64.7^{C}	66.0^{B}
≥5	59.6^{Aab}	59.2^{Aa}	58.0^{Aa}	64.3^{ABb}

^{a,b,c,d} Means within line without common lowercase superscript letter are significantly different ($P < 0.05$)
^{A,B} Means within column without common uppercase superscript letter are significantly different ($P < 0.05$)

2.6. Discussion

The distribution of milkings across the 24 h period clearly demonstrated a variation in the RR system utilisation when being operated with voluntary, distributed cow traffic. This is in agreement with previous results that have shown the relatively uneven distribution of the milkings in pasture-based grazing systems (Kerrisk 2010). Seasonal and split calving systems are still common management practices in Australia and are most predominant in Victoria and Tasmania (Dairy Australia 2009). These calving patterns result in fluctuations in herd size (and therefore machine utilisation levels) at certain times of the year.

As the RR does not have an automatic cleaning function, milk quality challenges will be inevitable during periods of low utilisation. Magazines that remain idle for an extended period of time after a milking, will undoubtedly have an increase in bacteria growth during the idle period. When the next milking occurs through these magazines, the bacteria will be flushed to the vat with the freshly harvested milk, resulting in increases in total plate count of the bulk milk. Magazines that remain idle for a settable period of time can be automatically disabled so that they are not used for milk harvesting until a system wash is conducted. However, automatic deactivation needs to be carefully managed so that the system does not 'run out' of available bails. A potential solution to this challenge is to operate the system with less active bails which reduces the chance that any bails remain idle and become deactivated. This would also allow the user to activate more 'clean' bails throughout the day or night as required. As a management tool this is deemed to be a potentially viable solution although concerns are held for the impact of this on cow traffic. It is known that cows respond positively to predictable circumstances and since they would be unlikely to be able to predict which bails are active vs. inactive (when only a proportion of bails are active) a negatively impact on the voluntary cow traffic onto the platform may result. As the user can choose the sequence of bails to activate the potential exists to have activated consecutive or alternate bails (or some other sequence).

The potential impact of the different sequences on both cow traffic and system efficiency was investigated and is reported in Chapter 3–E*ffects of bail activation sequence and feed availability on cow traffic and milk harvesting capacity in a robotic rotary dairy*.

The data presented in this Chapter indicates a higher than desirable proportion of incompletes which is of concern to researchers and developers alike. Gygax et al. (2007) showed successful attachment results in groups of cows milked with two different conventional AMS, of 94.5 and 97.5%. However, recognition of the fact that the RR is a different design to the AMS used in the study of Gygax et al. (2007) is essential. The aim of the RR system is to maximise the throughput potential, and therefore any unsuccessful teat cup attachment was not followed with a second attempt for attachment, even whilst the cow is still in the ACA bail position. An unsuccessfully attached cow is drafted back to the pre-milking holding yard to allow a second milking attempt to be conducted. In comparison, AMS box units are able to carry out several attempts on attachment, as the robotic device is fixed and can remain with the cow for the entire milk harvesting session (or return to the cow in a multi-box installation). Cows on the RR are rotated around the system and any additional time dedicated to reattachment of any missed teats on a 'difficult' conformation udder would hold up the system, decreasing the system throughput. An unpublished investigation was conducted with the prototype RR whereby operators manually instructed the ACA to reattempt attachment when an incomplete attachment occurred. The results showed that up to 50% of the missed teats could be attached successfully (similar to 2nd attempt results presented above) while the cow was still in the attachment bail without any negative impacts on other teats being milked. An increased attachment time was observed but this increase was significantly less than that associated with having the cow re-enter the system and occupying a bail for a full reattachment attempt. A change to the software to allow the ACA to take additional attempts at attachment could be a potential solution to address the less than ideal attachment accuracy that is reported in some investigations in this thesis. However, the potential improvements are also at risk of being eroded if farmers choose to deactivate the TPM or take the decision to not install a TPM.

It is known that teat cleaning before milking stimulates the release of oxytocin (OT), which in turn induces milk ejection (Bruckmaier et al. 2001). Premilking teat preparation, and the associated milk ejection, could increase the success of automatic cup attachments as a result of the increased teat and udder distension that is created by the process, thereby creating more 'defined' teats. As the TPM will be optional for farmers to purchase, it was deemed necessary to assess what the effects are on the attachment accuracy of not using a premilking teat preparation device. Attachment success was shown (above) to be significantly affected by parity, MI and 1st vs. 2nd attempt. Back quarters were also shown to be associated with a significantly higher risk of not being attached and of having longer attachment times. These challenges could increase even further if a premilking teat preparation device is not installed. The literature has previously shown that back quarters are more difficult to be attached for an automatic cup attachment device. This differences in attachment success between front and back quarters was recognised (albeit not quantified) in studies with a single-box AMS (Capelletti et al. 2004; Hamann et al. 2004). The effects of premilking teat preparation with a 'teat-cup-like' device on attachment accuracy and milk removal is therefore tested and reported in Chapter 4.

Results presented above indicated that MI was a significant factor in attachment success (at both 1st and 2nd attempt) and attachment speed. This is not unexpected as MI affects the volume of milk accumulated in the udder and therefore udder distension. A study by Bruckmaier and Hilger (2001) showed the relation between MI and milk ejection, in which a MI < 8 h resulted in an increased lag time of the milk let down process, essentially the effect of degree of udder fill. Milking interval in relation to level of udder fill has also been reported by Knight et al. (1994) and Stelwagen et al. (1996), this relationship could result in attachment differences when cows are milked with an increase milking interval after an incomplete milking. Whilst reducing the absolute number of incompletely attached cows (at 1st attempt) is a primary focus, a secondary focus is to determine optimal management practices for the incomplete cows. Two different management strategies were tested on whether or not the extension of the interval to a second milking attempt improved milking success of incompletely milked cows. This work is presented and discussed in Chapter 5.

2.7. Conclusions

This Chapter described in detail the functions and capabilities of the prototype RR. The challenges identified within the analysis constitute the basis of the research program reported in this thesis. This study showed that whilst the RR is operational with voluntary cow traffic, the system utilisation is reduced at specific times of the day, resulting in a decreased harvesting capacity of the system. It is also concluded that the success levels of teat cup attachment on the prototype RR was lower than desirable. Addressing potential solutions for these reported challenges constitutes the overall aim of this thesis.

Based on key issues indentified in this exploratory study, this thesis focuses on three main topics; (1) coping mechanisms for periods of *underutilisation* of the RR to increase potential for harvesting of high quality milk; (2) understanding the impact of premilking teat preparation on *attachment accuracy* to ensure farmers are well informed when deciding whether or not to install a TPM*;* and (3) development of optimal *management strategies* of incomplete milked cows and associated implications for dairy layout.

Chapter 3. Effects of bail activation sequence and feed availability on cow traffic and milk harvesting capacity in a robotic rotary dairy

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Overview of Chapter 3

The absence of an automatic plant cleaning function was outlined in Chapter 2. Whilst daily routines can accommodate this with regard to full system washes, the challenge is dealing with periods of low utilisation and idle periods between scheduled system washes. With no auto-rinsing function the potential exists for a build-up of bacteria in the plant if fresh milk is not regular flushed through the equipment. Periods of underutilisation of the system are largely created by the specific conditions associated with operating the system with voluntary cow traffic. It is known that utilisation of the system is lower during the night as a result of decreased voluntary cow traffic; these periods are associated with the rest period of cows in which activity is typically reduced. In addition management resulting in fluctuating herd size will also impact utilisation levels.

The overall goal of Chapter 3 is to investigate a coping mechanism to ensure that collection and storage of high quality milk can be maintained during periods of underutilisation of the system. Of particular interest is the impact of the coping mechanism or management strategy on cow traffic.

Effects of bail activation sequence and feed availability on cow traffic and milk harvesting capacity in a robotic rotary dairy

3.1. Abstract

This study was conducted to investigate the effects of different bail activation sequences in combination with feed availability on cow traffic and harvesting capacity in a novel prototype robotic rotary (RR; DeLaval AMR™). The RR can milk up to 50 cows per hour. However, in voluntary cow traffic systems like FutureDairy's farm in Australia, the number of cows presenting themselves may be low at certain times of the day (or seasons in seasonal calving systems). In these circumstances the ratio of active bails to the number of cows available may be undesirably high with consequential negative impacts on system efficiency and milk quality (the RR does not flush individual units automatically after each milking). Activating only 50% of the bails may be a management strategy chosen to cope with periods of underutilisation. Four treatments with a total activation of 50% (8) of bails (activation sequences of EIGHT, FOUR, TWO or ONE consecutive bail(s)) with or without the presence of feed on the RR were implemented during 16 four-hour observation periods after a system wash. No significant differences were observed in the proportion of available bails remaining idle across the four bail activation sequences. However, a significant interaction between the availability of feed and the number of cows in the holding yard (HY) showed that a bail was up to 48 times more likely to be utilised when feed was available and the number of cows in the HY was ≥ 49 compared to when feed was absent and < 49 cows were in the HY. Cows were 63 times more likely to hesitate to enter the platform when there was no feed available, the bail activation treatment was ONE and the number of cows in the HY was < 49 compared to when there was feed available in treatment ONE and there were ≥ 49 cows in the HY. In contrast, when feed was available and there were < 49 cows in the HY, treatment TWO was more likely to result in cow factors related idle time as cows were hesitating more to enter the platform compared to the other treatments. Overall, the presence of feed had a larger impact than bail activation sequence on cow traffic although the latter impacted significantly on the RR milk harvesting rate with, more consecutive bail activations resulting in more robot operations being conducted simultaneously and more milk harvested per minute of robot operation time. These results suggest that a feeding function on entry to the RR platform, in combination with bails activated sequentially, will lead to a more efficient use of the RR.

Additional keywords*:* automatic milking system, dairy, robotic rotary, harvesting rate

3.2. Introduction

Farms in predominately grazing countries have begun to install automatic milking systems (AMS; Kerrisk, 2010a). The farms in general have larger herds, lower milk yields and a higher efficiency of labour utilisation than many of the intensively fed and housed farming systems in which AMS are typically installed. In response to the specific requirement of larger scaled, pasture-based systems, a novel robotic rotary (RR; DeLaval automatic milking rotary–AMR™, Tumba, Sweden) has been developed and was installed at the Elizabeth Macarthur Agricultural Institute (EMAI, Camden, NSW, Australia) in 2009 with co-development and testing ongoing since then. The RR was initially developed to be able to milk a large herd of cows automatically with a lower capital investment compared to the existing, single- and multi-box, AMS technology.

The RR is capable of carrying out in the order of 50 cow milkings per hour with the installation of two robots: (1) a teat preparation robot (teat preparation module; TPM), and (2) a teat cup attachment robot (automatic cup attacher; ACA). To enable the RR to achieve such high levels of throughput (compared to a single-box robot) the robotic arms remain stationary whilst the rotary platform rotates the cow around from the entry point to the exit point in a stop-start operation (See Figure 3.1). The installation of multiple robotic arms enables two cows to be simultaneously cleaned and attached, resulting in a higher potential throughput (compared to existing commercial AMS units).

Two of the key functionality differences between existing commercial AMS units and the RR are: (1) The RR has no automated washing or rinsing functionality; and (2) the RR does not have an integrated controlled feeding function. Incorporating these two functions may be technically achievable but the cost of the additional automation may be cost prohibitive. The RR was initially developed to create an economically attractive solution for larger scaled farms to automate the milk harvesting tasks. The financial advantage of the RR compared to traditional AMS will likely be eroded if additional functionalities are incorporated. It has been recognised that at least the first commercial versions of the equipment will not have these two functions (R. Mulder, DeLaval, pers. comm.).

The lack of automated washing will create the greatest application challenge when the system is being under-utilised with regard to number of cows in milk or number of milkings conducted per day. To cope with the potential impact of individual used bails being idle (and the associated increase in bacteria count) an auto-disabling function is available which allows the user to set the idle time limit prior to the used bail being deactivated. During periods of underutilisation, the ratio of cows to active bails will be low and bails will have an increased risk of being deactivated. In extreme circumstances this will result in very low numbers of active bails within a small number of hours after a system wash has been implemented. A potential solution is to increase the ratio of cows to active bails by deactivating some bails. This will reduce the risk of bails being automatically deactivated whilst also ensuring that clean bails can be manually activated as required. This should allow the system to be operated efficiently throughout extended periods (up to 12 hours) between system washes.

It has been reported that cows, as animals of routine, are conditioned by circumstances surrounding milking (Cowie, 1983 cited by Stefanowska, Ipema and Hendriks 1999). It is possible that the configuration of active bails (e.g. alternate, or groups of consecutive bails referred to as 'bail activation sequence' throughout this chapter) may impact predictability for the cows thereby affecting cow traffic onto the platform. In addition the efficiency of the robotic devices may also be affected by reducing the likelihood of robotic arm actions being conducted simultaneously.

The lack of in-bail feeding has the potential to impact on cow traffic and the speed at which cows traffic onto the platform. Numerous reports in the literature have shown the impact of concentrated feed (Halachmi et al. 2005; Bach et al. 2007) and even pasture allocation (Jago et al. 2002; Davis et al. 2007) as motivators for cow traffic.

It was hypothesised that a consecutive bail activation sequence and the presence of in-bail feeding would result in improved cow traffic and in more efficient robot operation thereby improving the overall potential and actual throughput and the milk harvesting rates of the prototype RR.

3.3. Materials and methods

3.3.1 Experimental design

The RR conducts a defined process to carryout milk harvesting prior to a cow being released from the RR platform. See Appendix as section 3.8 in this chapter for a detailed description of the RR milking process. The milking process in the 16 bail prototype RR with two robots is, in brief, as follows (refer to Figure 3.1 and Chapter 2 for more details): (1) a cow is 'recognised' upon entry; (2) if the "buffer zone" (numbered as bail 16 in Figure 3.1) is already occupied, the cow waiting at the gate will not gain access until the next available bail rotates to the entry gate position (bail 1 in Figure 3.1); (3) after entering, the cow is rotated towards the TPM for premilking teat preparation, (shown as bail 15 in Figure 3.1); (4) the cow is rotated from TPM to

ACA where teat-cups are attached (shown as bail 14 in Figure 3.1); (5) the cow is rotated towards the exit of the RR platform in a step-wise fashion.

When a cow is still being milked as she enters the “safe zone” (shown as the grey bar alongside bail 4 in Figure 3.1) rotation is prevented and all other actions are paused until the milking of that cow is complete. When no cows enter an available bail in the buffer zone, the system waits for up to 90 sec (settable time) after all robot functions are complete and the cow in the safe zone is finished milking before a step time out occurs (STO; available bail will remain unutilised).

Figure 3.1: Schematic of the RR showing; the entry to the rotary, the buffer bail zone, teat preparation module (TPM; in yellow), automatic cup attacher (ACA; in grey), the safe zone (bail 4), exit from the rotary platform and the feed available at the TPM and buffer bail positions (bails 15 and 16, two separate feed bins are positioned as indicated by the black circles; schematic graphic user interface of AMR™; courtesy of DeLaval)

During the trial, 160 mixed breed (Holstein x Illawarra, Holstein Friesian and Illawarra) dairy cows were managed as a single voluntarily trafficking herd and milked with a prototype RR. The herd consisted of 30% primiparous and 70% multiparous animals, with an average of 3 lactations (parity range 1–10; median lactation number 2; SD 2.1) and 137 days in milk (median 140 d; SD 88.9 d). At the commencement of the trial the 7-day average production level of the cows was 18.5 kg/cow per day (median 17.8 kg; SD 6.3 kg), average yield per milking was 10.8 kg/cow per milking (median 10.3 kg, SD 5.5 kg) and average milking frequency was 1.7 milkings/cow per day (median 2; SD 0.4). All the cows had up to 18 months intermittent, regular exposure and experience with the RR prior to the start of the trial. The RR was continuously operated in a voluntary distributed manner for six weeks prior the commencement of the trial.

The cows had access to a day pasture break from 0830 to 1800 h and a night pasture break from 1800 to 0830 h. Total feed allocation target was 20 kg DM/cow per day, with 6 kg DM/cow per day supplied as partial mixed ration (PMR) on the post-milking feedpad. The PMR consisted of 3.7 kg maize silage, 1.3 kg pelleted concentrate (18% protein), 0.5 kg oaten hay, 0.4 kg lucerne silage and 0.1 kg oaten silage (all as kg DM/cow.day). As presence of feed was also investigated during this trial; during "feed-on" periods cows were given an additional small allocation of pelleted concentrate (18% protein) in the first two bails of the RR (total ~0.3 kg/cow per milking; bail 15 and 16 as shown in Figure 3.1).

Cow traffic in this chapter refers to voluntary movement of cows around the farm resulting in a milking without human encouragement. To test the impact of the different bail activation sequences on cow traffic onto the prototype RR and robotic harvesting efficiency, four different bail activation sequence settings were tested (Figure 3.2): (1) Eight consecutive bails activated (EIGHT); (2) two sets of four consecutive bails activated (FOUR); (3) four sets of two consecutive bails activated (TWO); and (4) every alternate bail activated (ONE).

To determine the impact of the availability of feed (pelleted concentrates available to cows on entry to the RR; see Figure 3.1) on cow traffic onto the RR, feed availability (no feed available versus feed available) was tested in combination with the four different bail activation treatments. A five-day adjustment period was implemented when the feed was turned off prior to starting observations and a two-day adjustment period was given when feed was reoffered after the non-feeding treatment.

Each treatment was randomly selected per block and was repeated and observed twice, with and without feed (Table 3.1). A block was defined in this chapter as the period of consecutive days when observations were conducted. Every block was designed to contain four treatments in the initial study design. However, due to system failure (a breakdown) the first block contained only two treatments. The two treatments missed in this block were applied in the fourth block. In total 16 four-hour observations were conducted with each session commencing in the morning after a system wash at approximately 0700 h.

The following data were collected manually and recorded during the observation periods: (1) The occupancy of each bail on each rotation (supported by electronic data). (2) 'Cow related idle times'. *Idle time* was defined as any time when the system was capable of conducting a certain action (e.g. teat cleaning, cup attaching or platform rotation) but that action was delayed as a result of cow traffic, milking duration or a technical function. There were three 'cow factor' idle times; (a) a cow did not walk on the platform and a STO occurred; (b) a cow hesitated and was standing in the entry gate preventing platform rotation; and (c) a cow did not walk on the RR during the buffer period (period during which at least one robot was conducting an action and the platform could not rotate) but walked onto the platform prior to a STO occurring. (3) There were two ‘system factor’ idle times: (a) if the entry gates did not allow a cow to enter the system during the buffer period. The last consecutive active bail in any sequence was denied a buffer period. By default this meant that bails 3, 7, 11 and 15 in treatment TWO, bails 3 and 11 in treatment FOUR and bail 11 in treatment EIGHT did not have a buffer period (referring to bails shown in Figure 3.2); and (b) rotation prevented due to a cow still being milked (milking in progress) when reaching the exit point of the platform. Milking in progress was deemed a system factor idle time since it was influenced strongly by the bail activation sequence. Whilst the potential for this to occur with slow milking cows in any bail of any of the four bail activation sequences existed, the likelihood was greatest for treatments EIGHT and FOUR as cows entering the last of the consecutive active bails were rotated to the exit area more promptly. And lastly (4) the net number of cows waiting in the pre-milking holding yard (HY; 118.6 m^2) was recorded manually every full rotation of the rotary platform.

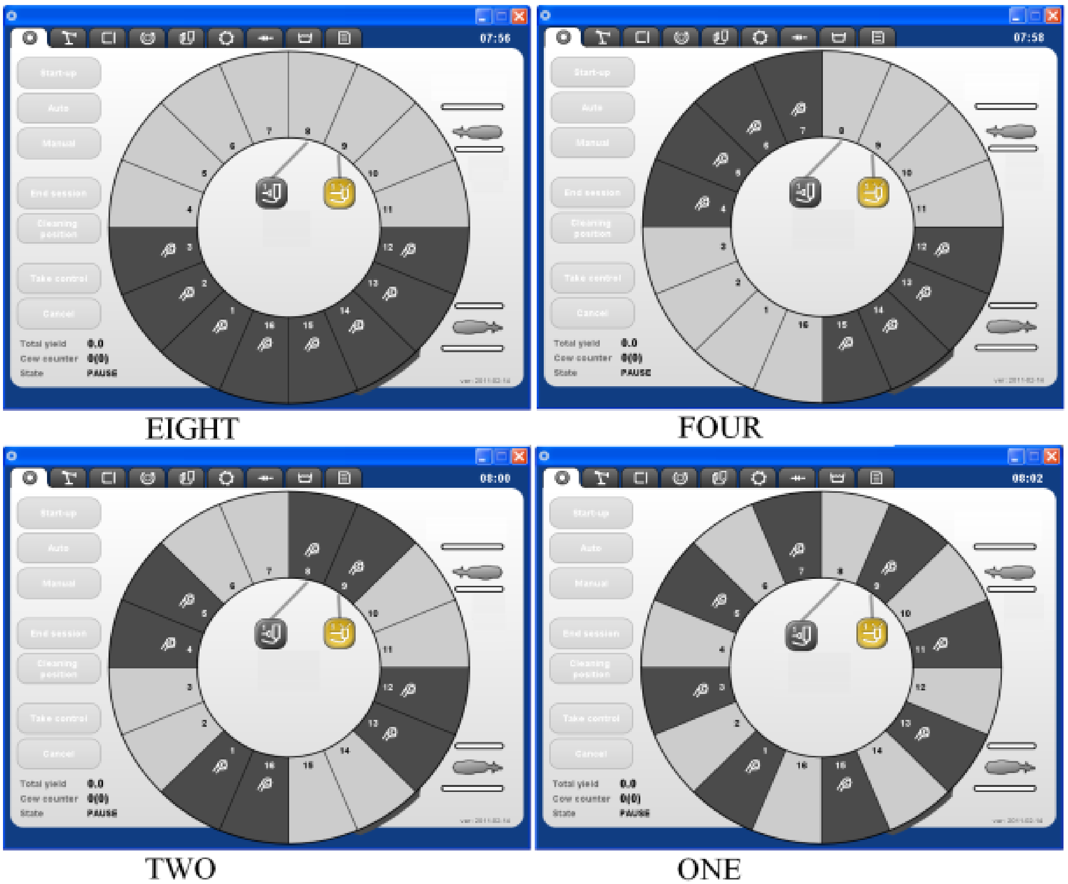

Figure 3.2: Four bail activation sequences treatments tested, where dark coloured bails are inactive and light coloured bails are active (schematic graphic user interface of AMR™; courtesy of DeLaval)

Table 3.1: Trial design

	Block	#1		# 2				# 3				# 4					
	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Treatment	No feed			TWO	ONE	EIGHT	FOUR	EIGHT	TWO	FOUR	ONE						
	Feed	ONE	EIGHT									FOUR	TWO	ONE	TWO	FOUR	EIGHT

Block 1 had only 2 treatments due to a system breakdown. These were applied in block 4

The STO time was set at 90 sec for the duration of the trial and all four treatment groups had eight bails active during the entire four-hour observation sessions. Bails remaining idle were not disabled during the observation periods. This decision was made to allow the designated bail activation sequence (treatments) to be maintained for the entirety of each observation period.

3.3.2 Statistical analyses

3.3.2.1 Outcome variables

Treatment impacts were measured on four binary outcome variables: (1) utilisation of available bails; (2) occurrence of an idle time due to *cow* factors (*cow–idle time; yes/no*); (3) occurrence of an idle time due to *system* factors (*system idle time*; *yes/no*) and three quantitative outcome variables; (1) duration of *cow–idle time*; (2) duration *system idle time*; and (3) harvesting rate (kg/min *robot operation* time).

Harvesting rate. Electronic data collected by the VMSClient management program (DeLaval, Tumba, Sweden) were used to calculate the total milk yield harvested per observation period which was then used for calculation of the harvesting rate:

Harvesting rate (kg/min *robot operation time*) = Total yield per observation period divided by robot operation time

Robot operation time was the total time of the four-hour observation period that the RR was capable of operating, minus idle times related to *cow factors*. Cow related idle times were deleted from the robot operation times to generate a harvesting rate that is calculated in a similar manner to that commonly reported with single and multi-box AMS (milk harvested/min of crate occupancy). As a parameter, harvesting rate gives the reader an indication of the potential harvesting rate of the system assuming cows are presenting themselves onto the RR without delay.

To calculate system harvesting rate, all data were summarised per hour of the observation.

3.3.2.2 Explanatory variables

Treatment, feed availability and the number of cows waiting in the pre-milking holding yard (HY) were used as explanatory variables in all analyses. The number of cows in the HY is a net result of the number of cows entering the HY from the paddock and cows exiting the HY, by entering the RR. It was found that on average 12.0 and 11.3 cows per hour entered the HY voluntary, for the 'no feed' and 'feed' treatments respectively.

3.3.2.3 Statistical models

Data were analysed with GenStat 13th Edition (VSN International, Hertfordshire, UK). Binary outcome variables were analysed using generalised linear mixed models (GLMM) and continuous outcome variables using restricted maximum likelihood models (REML). Bail activation sequence, feed availability, number of cows in the HY and their first order interactions were included as fixed effects while block and day within block were included as random effects in the models. Non significant terms were deleted from the final model but treatment and feed availability, the variables of interest, were retained in the final model, even if not significant. The net number of cows in the HY was categorised for all models into two categories: < 49 cows and ≥ 49 cows in the pre-milking HY as it was not able to meet the assumption of linearity. The choice of this value (49) was based on the restricted cubic spline analyses which showed that with ≥ 49 cows in the HY the probability of a bail being utilised declined and that with lower net numbers of cows in the HY, of up to 49 cows, the proportion of bails being utilised was constant.

For analyses of cow and system related idle times, the observations where no idle time occurred were excluded and then the outcome variables were log transformed to normalise their distributions.

3.4. Results

3.4.1 Descriptive results

Regardless of the sequence of bails enabled/disabled, the proportion of available bails that were actually used during all the observed milkings was relatively consistent between treatments ($P > 0.05$; range 71% to 77%; Table 3.2). However, the impact of feed on the proportion of available bails being used was significant ($P < 0.05$; 59% vs. 90% for no feed vs. feed respectively). Table 3.3 shows the incidence and total duration of idle time events recorded across the 16 observation sessions related to cow and system factors.

Table 3.2: Proportion of available bails (active bails passing the entry point) occupied by cows per treatment, with or without feed available

	EIGHT	FOUR	TWO	ONE	Overall
No feed	0.60	0.59	0.65	0.54	0.59
Feed	0.88	0.94	0.89	0.89	0.90
Overall	0.74	0.77	0.76	0.71	0.74

Table 3.3: Number of events and total duration (min) of cow and system related idle times for all 16 observation sessions, shown per treatment

Bail	Cow idle		System idle	
treatment	n	Time (min)	n	Time (min)
EIGHT	120	192.3	69	24.9
FOUR	118	175.7	97	15.7
TWO	137	174.3	164	38.8
ONE	112	173.3	8	1.7

3.4.2 Cow traffic onto the robotic rotary: utilised vs. not utilised bails

The probability of an available bail being utilised was affected by feed availability but not by the bail activation treatment (Table 3.4). There was a significant interaction between the feed availability and number of cows in the HY which suggested that the odds of bail utilisation were up to 48 times higher when feed was available and number of cows in the HY was ≥ 49 compared to when feed was absent and < 49 cows were in the HY.

Table 3.4: Final generalised linear mixed model for the binary outcome variable utilisation of available bails by cows trafficking onto the robotic rotary platform

Effect	Categories	Parameter estimate	Standard error	Odds ratio (95% CI^)	P-value
Intercept		0.32	0.42		
Bail treatment					0.852
	EIGHT	0.00			
	FOUR	0.17	0.37	1.18 (0.57, 2.46)	
	TWO	-0.12	0.37	0.89 (0.43, 1.85)	
	ONE	-0.13	0.37	0.88 (0.42, 1.83)	
Feed availability					0.001
	No feed	0.00			
	Feed	1.56	0.52	-	
Number of cows in holding yard					0.0017
	0–49	0.00			
	≥49	0.12	0.38	-	
Feed availability × Number of cows in holding yard					0.004
	Feed × ≥49	2.19	0.77	-	

^Confidence interval
Block and day nested in block were included as random effects

3.4.3 Cow factors resulting in idle time

The availability of feed by treatment and the availability of feed by number of cows in the HY interactions were both significant in the occurrence of cow factor idle times (Table 3.5). The odds ratio results presented in Table 3.6 suggest that when feed was available (and there were ≥ 49 cows in the HY) treatment TWO was 6.4 times more likely to result in cow idle time compared to the ONE bail activation treatment (with feed available and ≥ 49 cows were in the HY). When more cows were waiting for milking and feed was available, a significant reduction in cow related idle times occurred.

Table 3.5: Final generalised linear mixed model for the binary outcome variable–occurrence of idle time events due to *cow* factors

Effect	Categories	Parameter estimate	Standard error	P-value
Intercept		0.41	0.58	
Bail treatment				0.291
	EIGHT	0.00		
	FOUR	0.19	0.50	
	TWO	0.13	0.50	
	ONE	0.29	0.50	
Feed availability				0.013
	No feed	0.00		
	Feed	-2.02	0.84	
Number of cows in holding yard				0.004
	0–49	0.00		
	≥49	-0.20	0.23	
Bail treatment × Feed availability				0.049
	FOUR × F	0.17	0.80	
	TWO × F	1.62	0.82	
	ONE × F	-0.40	0.76	
Feed availability × Number of cows in holding yard				0.001
	F × ≥49	-1.53	0.47	

Block and day nested in block were included as random effects

Table 3.6: Odds ratios of the interactions between bail treatment × feed availability and feed availability × number of cows in the holding yard

Bail treatment	Number of cows in holding yard <49 cows		Number of cows in holding yard ≥49 cows	
	No Feed	Feed	No Feed	Feed
EIGHT	47.4	6.26	39.0	1.1
FOUR	57.4	9.03	47.2	1.6
TWO	53.9	35.94	44.3	6.4
ONE	63.1	5.61	51.9	*1.0

*Reference category

It was found that the feed availability (average odds ratio; no feed = 50.5; feed = 8.6) had a stronger influence on the likelihood of cow related idle events compared to the number of cows in the HY (average odds ratio; 0–49 = 34.8; ≥ 49 = 24.3) in the interaction between these two variables. Despite this interaction being significant, it was evident that the effect of feed availability on the occurrence of idle time events due to cow factors was of higher magnitude compared to the number of cows in the HY, with a similar effect of cows in the HY with or without the availability of feed (difference in odds between cows in HY; no feed 9.8; odds 55.5–45.6, and feed treatment 11.2; odds 12.2–2.50).

Feed availability did not significantly affect the length of idle time due to cow factors (77.4 sec when no feed was available and 69.3 sec when feed was available); however, bail treatment had a significant effect as shown in Figure 3.3. Treatment EIGHT had the highest idle duration per event with 80.3 sec, followed by treatment ONE, FOUR and TWO with 78.6, 70.5 and 64.7 sec respectively. The assumption of equal variances was valid in the final model, however the assumption of normally distributed residuals was slightly invalid as they peaked around 0 (as most of the idle times occurring were around 90 sec; set as maximum STO). However, the model is more robust to the assumption of normality due to the properties of the central limit theorem.

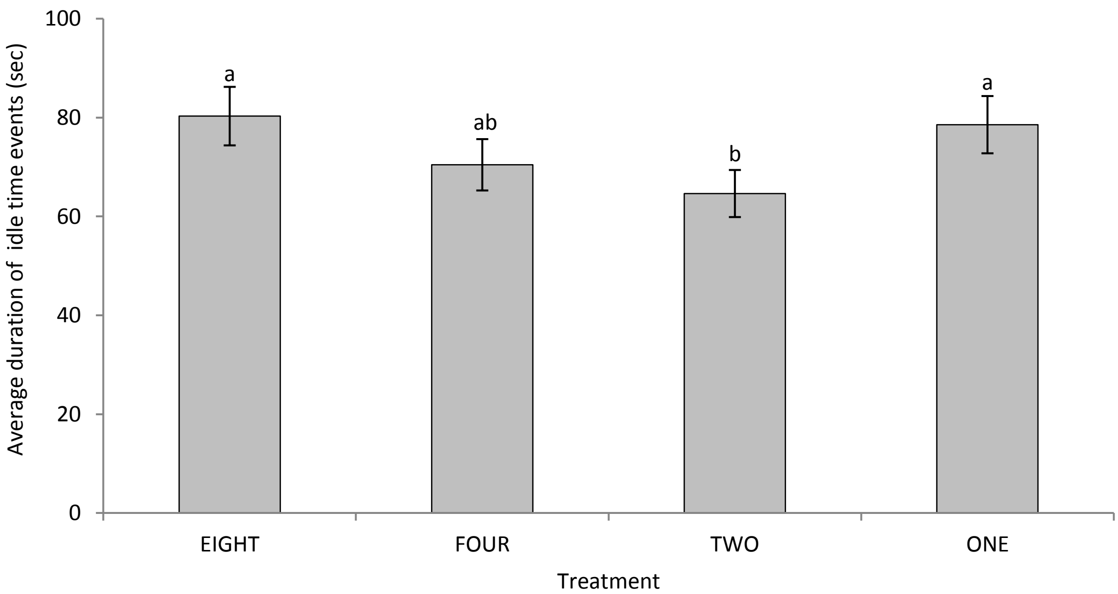

Figure 3.3: Average duration of idle time events related to cow factors. Vertical bars indicate SEM (standard error of the mean). Different letters indicate a significant treatment effect (P < 0.05)

3.4.4 System factors resulting in occurrence of idle events

The results of the final GLMM model showed a significant affect of bail activation treatment on the incidence of system related idle times. As shown in Table 3.7, treatment TWO was 4.82 times more likely to cause a system related idle time compared to treatment EIGHT whilst treatment ONE resulted in the lowest incidence of idle time events related to system factors. The likelihood of system related idle events occurring increased significantly with more cows in the holding yard and availability of feed. No interaction term was significant.

Table 3.7: Final generalised linear mixed model to investigate the probability of an idle event occurring due to system factors

Effect	Categories	Parameter estimate	Standard Error	Odds ratio (95% CI^)	P-value
Intercept		-2.08	0.22		
Bail treatment					<0.001
	EIGHT	0.00			
	FOUR	0.59	0.21	1.80 (1.20, 2.71)	
	TWO	1.57	0.21	4.82 (3.21, 7.22)	
	ONE	-2.23	0.39	0.11 (0.05, 0.23)	
Feed availability					<0.001
	No feed	0			
	Feed	1.04	0.19	2.82 (1.93, 4.14)	
Number of cows in holding yard					0.041
	0–49	0			
	≥49	0.35	0.17	1.42 (1.02, 1.98)	

^Confidence interval
Block and day nested in block were included as random effects

There was no significant effect of the bail activation sequence (P = 0.21) or the availability of feed (P = 0.10) on the duration of idle time events.

3.4.5 Harvesting rate

Treatment ONE resulted in a significant decrease of the system harvesting rate (kg per minute robotic operation time; kg/min) compared to the other treatments (Figure 3.4). The availability of feed did not affect the harvesting rate in the final model.

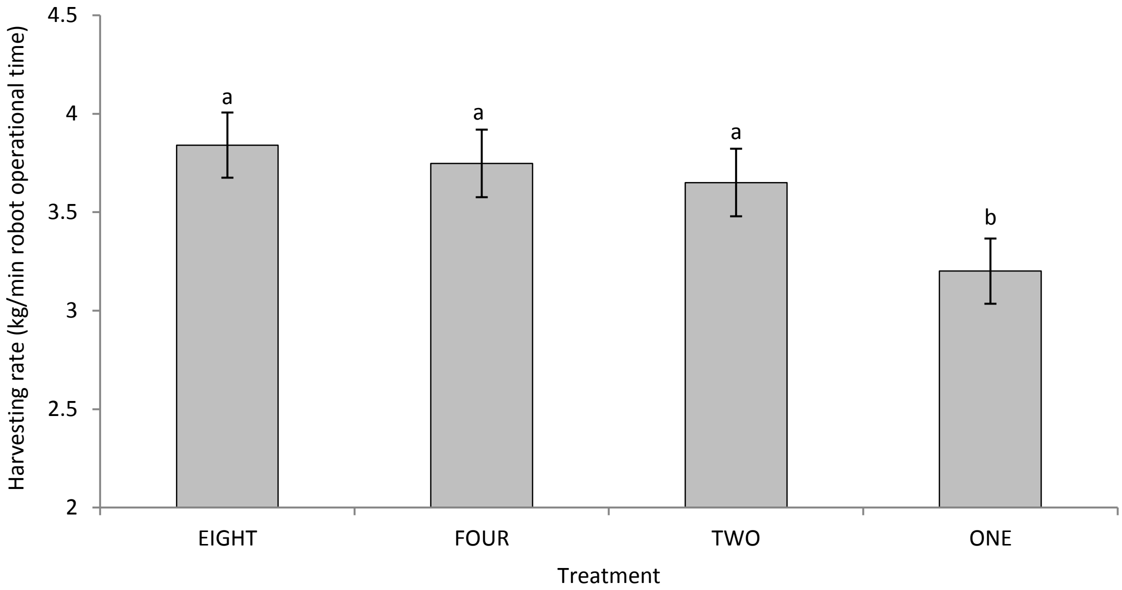

Figure 3.4: Robot operational efficiency; harvesting rate per treatment. Vertical bars indicate SEM (standard error of the mean). Different letters indicate a significant treatment effect (P < 0.05)

3.5. Discussion

Utilisation of available bails was not influenced by bail activation sequence. However, the availability of feed had a significant impact on bail utilisation. Despite the incorporation of a 5-day habituation period after removal of the feed, it is recognised that all of the cows in the study were familiar with feed on the RR. Although the impact of feed availability on inexperienced cows being adapted to the system is unknown, the results suggest that an ability to provide feed on the RR design would likely be beneficial and should be included in the design of the RR dairy. A study by Prescott et al. (1998b) suggested that feeding in AMS is likely to be necessary to motivate cows to visit an AMS. Their research showed that feed was significantly more rewarding for a cow than milking itself. A more recent study by Melin et al. (2006) with 24 cows concluded that both milking and feeding acted as rewards for cows encouraging them to present themselves to the AMS, however the motivation to access feed had a higher priority than the motivation of being milked.

When investigating the incidence of cow factors idle time, interestingly there was a significant interaction found between bail activation sequence and the availability of feed. Cows tended to wait longer before entering the platform, with treatment TWO when feed was available compared to treatments EIGHT, FOUR and ONE treatment. With treatment TWO, four bails had no buffer period which meant that the gate remained closed for a cow until the TPM was finished with the cleaning task. This may have reduced the cows' ability to predict the accessibility thereby resulting in cows being more cautious to enter the system. It is therefore suggested that cows should be granted access to the platform as soon as possible after a rotation to minimize the impact on cow traffic. In other words, all bail activation configurations should allow cows to access the platform during the buffer period when the TPM and/or ACA are operating.

A significant interaction was also found between availability of feed and the number of cows in the HY. It was shown that with feed and more cows in the HY, the incidence of cow related idle times were reduced. Previous research has shown the importance of social dominance in a voluntary automated system. A study of Ketelaar de Lauwere et al. (1996) showed that the time a cow spent in the pre-milking HY might be influenced by dominance of cows. Dominance-related behaviour has also been shown to be more evident when cows are offered unrestricted amounts of feed (Pedernera 2008). It is possible that when more cows were in the milking queue and a feed reward was available, the dominant cows found it more challenging and less appealing to restrict access of their herd mates to the RR.

To alleviate any concerns regarding the potential confounding of the feed availability on the net number of cows in the HY, we estimated the average rate of voluntary cow traffic entering the herd in the HY. This rate was 12.0 and 11.3 cows/h respectively for no feed and feed treatments suggesting that cow traffic from the paddock was not modified by the provision of a small amount of concentrates upon the entry of the RR.

Despite a significant interaction between feed availability and number of cows in the HY the magnitude of the effect of feed was larger than that of the cow queue size. This is comforting as providing a feed reward is likely to be deemed as an acceptable management option to adopt to encourage voluntary cow traffic. On the other hand ensuring cow queues are consistently large is less appealing and could have associated negative impacts on the productivity of the farm system.

Different bail activation sequences significantly affected the probability of *system* related idle times, as did the number of cows in the HY and feed availability. Treatment TWO resulted in the highest proportion of system related idle times. This was also likely caused by the fact that with this treatment a cow could not enter the platform during the buffer period. Treatment ONE had the smallest incidence of system related idle times, as cows were always able to use the buffer period of the system and the occurrence of cows which were still being milked as they approached the exit area of the platform was very low, particularly compared to treatment

EIGHT. During treatment EIGHT there were nine incidences when a cow was still being milked as she approached the exit area. This was predominantly caused by the fact that cows that entered the 6th, 7th or 8th consecutive active bail (see Figure 3.2) were rotated to the exit area promptly as the subsequent bails were deactivated and did not wait for cow entry or TPM and ACA operations. However whilst there was a significant effect of system related idle times on the system utilisation, the magnitude of the impact of cow related idle times had a greater overall impact on the system throughput efficiency.

Whilst cow traffic was largely unaffected, harvesting efficiency was significantly impacted by the bail activation sequence. Harvesting efficiency indicates a potential amount of milk harvested per min robot operation time. The robotic devices of the RR operated most efficiently when consecutive bails were active. This was due to the fact that, when at least two cows were positioned in consecutive bails, the two robots (TPM and ACA) were operating simultaneously, which reduced the handling time and improved the harvesting rate. This resulted in a significantly lower harvesting rate of treatment ONE compared to the other treatments, and especially treatment EIGHT as a direct result of the number of simultaneous robot operations conducted. The availability of feed would also be expected to impact on the system harvesting rate as a direct result of a higher proportion of the available bails being occupied and therefore, more robot operations being conducted simultaneously. In the literature it is shown that the capacity of the single box AMS is limited by the fact that the robotic arm cannot attend to any other cows during the entire milk harvesting session of an individual cow. This lowers the harvesting rate, presented as total production per day divided by the total crate time (when a cow is present in the AMS crate), which is commonly reported to be around 1.25–1.85kg/min (de Koning 2011b). A study by Davis et al. (2008a) showed an increased harvesting rate from 1.74 to 2.08 kg/min when the handling time was reduced by not using the premilking teat cleaning function of the robot. The fact that the robotic arm in the RR does not remain with the cow during the entire milking process results in a higher potential throughput compared to traditional/commercially available AMS units. The results presented here show that harvesting rates up to 3.85 kg/min were recorded in this study with the prototype RR with 50% of the bails enabled.

It is important to note that all data presented in this chapter pertains directly to the prototype 16 bail RR. With ongoing development both prior to and after commercialisation the potential exists for the technology to improve with regard to efficiency and functionality. This means that the specific results like the harvesting rates presented in this study may become less aligned with data generated on commercial farms in the future. It should also be recognised that all data presented here were collected and calculated with only 50% of the bails activated and as a result cannot be interpreted as the maximum capacity of the system.

3.6. Conclusions

It was concluded that when half of the total bails were deactivated (to simulate periods of underutilisation), the sequence of active bails *per se* did not affect cow traffic onto the RR platform. The application of this finding is most relevant for periods when the herd size and total number of anticipated milkings are lower than the system capacity. However, the interactions observed in this study suggest that, in the future, efficiency could be potentially improved by having 'intelligent' systems that detect other factors (e.g. number of cows in the HY) and change bail activation sequence accordingly. The negative results of the absence of feed upon the entry of the RR indicate that cow traffic onto the platform was improved when feed was available. This suggests that when cows are accustomed to receiving feed during milking, regular provision of feed is important to ensure voluntary movement of cows onto the RR whilst avoiding cow traffic related delays. There are advantages to be gained through activating simultaneous bails rather than alternate bails to result in an increased milk harvesting rate through a higher proportion of robot operations being conducted simultaneously. Consecutive bails activated in combination with feed and will result in an increased efficiency of operation while managing the RR in an underutilised setting.

3.7. Acknowledgements

This work was carried out within the FutureDairy program. We wish to acknowledge the investors Dairy Australia, DeLaval, NSW Department of Primary Industries and The University of Sydney. We would also like to thank Mikael Karttunen for his technical support of the RR and the FutureDairy team for their assistance.

3.8. Appendix–robotic rotary dairy operational process

The RR will go through a series of actions to result in a cow being milked and released back into the herd. The detailed operational process of the RR is as follows:

(1) A cow presents herself at the *entry* and is electronically ‘recognised’ by her neck transponder

(2) If the first bail position (termed “buffer zone” and numbered as bail 16 in Figure 3.1) is already occupied, the cow waiting at the gate will not gain access until the next available bail (bail 1 in Figure 3.1) rotates to the entry gate position; this will not happen until all robot actions are complete. Cows receive their first ~150 g portion of pelleted concentrate whilst in the buffer zone position

(3) When robot actions are complete, the cow is rotated towards the first robot, the TPM zone (shown as bail 15 in Figure 3.1), where teats are cleaned, foremilk is removed and the milk let down is stimulated with a teat-cup-like cleaning device whilst a second portion of ~150 g feed is given and the bail that is now located in the buffer zone accepts another cow

(4) At the same time, teat cups are attached to the cow positioned at the ACA zone (in front of the ACA robot–shown as bail 14 in Figure 3.1)

(5) When both robots, the TPM and ACA are finished (and the second cow has entered the platform at the buffer zone), a rotation step will take the “prepared” cow to the ACA position (show as bail 14 in Figure 3.1)

(6) At the ACA zone teat-cups are collected from a “magazine” two at a time and are attached individually; every teat has a separate in-line milk meter that monitors milk volume (flow) and milk quality (conductivity and blood presence)

(7) The cow is rotated towards the exit of the RR platform in a step-wise fashion where she is expected to leave the platform (whilst subsequent cows enter the platform and go through the same premilking teat preparation and cup attachment process described above).

More details of the equipment functioning are shown in Chapter 2.

Chapter 4. The effect of premilking with a 'teat-cup-like' device, in an novel robotic rotary, on attachment accuracy and milk removal

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Overview of Chapter 4

Chapter 3 addresses the key issue of bail activation sequence and feed availability on system's performance. An alternative to increase efficiency is to reduce operational time by, e.g. not cleaning teats before milking. However, farmers will need to be informed of the function of components of the RR; particularly where knowledge level is likely to impact on decisions to install (or not install) optional components. One such optional component is the premilking teat preparation device (teat preparation module, TPM). This component has the obvious potential to impact on milk quality which can be alleviated by implementation of an alternative teat cleaning system. However, the potential impact on the milk harvesting efficiency of the system is investigated in Chapter 4 as it was identified in Chapter 3, as being of high importance in a high throughput AMS.

Investigating the effects of not using a premilking teat preparation device is the focus of Chapter 4. To allow a meaningful comparison between using a TPM or not, detailed quantification of the effects on attachment accuracy and milk removal characteristics between the two treatments (wash or no wash) are reported here to ensure farmers are well positioned to make an informed decision about the investment in a TPM.

The effect of premilking with a 'teat-cup-like' device, in a novel robotic rotary, on attachment accuracy and milk removal

4.1. Abstract

This study investigated the effects of premilking teat preparation on attachment accuracy and milk removal characteristics for individual cows in a novel 16-bail prototype robotic rotary (RR; DeLaval AMR™, Tumba, Sweden). The study was conducted as part of the FutureDairy project, the Australian national research program. The first commercial versions of the RR systems will have the *option* of purchasing and installing a teat preparation module (TPM) for premilking stimulation and cleaning of teats. It was expected that with the use of a TPM the attachment of teat cups would be faster and more successful and, milk removal efficiency, in terms of average and peak milk flow rate, would increase. There was a significant effect of treatment (no wash vs. wash) and individual quarters on attachment success as cows exposed to the wash treatment had up to 1.5 times higher odds of being successfully attached. The right front teats had 3.1 times higher odds of being successfully attached compared to the left back teat. The attachment was not only more successful but was also 4.3 s faster after cows were exposed to the wash treatment. A*verage milk flow* rate was not affected by the wash treatment. Nevertheless a significant interaction was found between the wash treatment and milking interval affecting *peak milk flow* (kg/min) of individual cows. This interaction showed that cows during the wash treatment, milked with a milking interval ≤ 8 h, had significantly higher peak flow rates (300 g/min increase) compared to no wash treatment cows. The relationship between premilking stimulation and attachment success shown in this study will increase the awareness (of both farmers and developers of the technology) of the importance of teat cleaning within the RR. The effects of the improved system performance should be taken into account (alongside the capital investment cost) when deciding to install a RR equipped (or not equipped) with a TPM. It is acknowledged that the effect of washing treatment on udder health and milk quality was not quantified in this study.

Additional keywords: attachment success rate, automatic milking system, robotic rotary, dairy

4.2. Introduction

Different methods of teat cleaning as a premilking solution are used by different AMS manufacturers. In the European Union udder cleaning and premilking teat preparation is a mandatory requirement[2]. Teat cleaning by wet horizontal rotating brushes, separate, 'teat-cup-like', cleaning devices and cleaning within the teat cup used for milking are all examples of premilking teat preparation solutions used in existing single- and multi-box AMS (Knappstein et al. 2004). It is known that premilking teat preparation creates the release of oxytocin (OT) and induces milk ejection (Bruckmaier and Hilger 2001). Studies have been carried out to investigate the suitability of AMS cleaning devices on premilking teat preparation and OT release. It has been generally concluded that AMS teat cleaning devices sufficiently stimulate the milk let down process for complete milk removal (Bruckmaier and Hilger 2001; Dzidic et al. 2004). Specific investigation into a system equipped with a separate, teat-cup-like, cleaning device, indicated no difference was found in OT levels when using cold (13–15°C) or warm water (30–32°C) for teat cleaning with both methods inducing milk ejection (Dzidic et al. 2004). A delay of attachment after cleaning in the AMS up to 4.3 min was not found to influence the milk let down process negatively (Macuhová et al. 2004). Because teat cleaning is not commonly practiced in Australasian dairy industries, studies have been conducted with single-box AMS to quantify the potential increased throughput that is generated when the teat cleaning devices are disabled. Time savings of 0.5 and 1.1 minute were realised per milking without a significant negative impact on teat cup attachment success (Jago et al. 2006a) or milk yield (Davis et al. 2008a).

The success rate of attachment in an AMS is of crucial importance. While the system is operational without human intervention, it is important that the AMS will perform reliable teat cup attachments (Frost et al. 1993). It is known that failures in teat cup attachment will affect the AMS capacity and milk production (Ipema and Stefanowska 2000; Bach and Busto 2005; Gygax et al. 2007). A study conducted by Bach and Busto (2005) showed that 7.6% of the total attachment attempts failed, without taking cow behavioural aspects into account (e.g. kicking). Another study showed similar attachment results in groups of cows milked with two different AMS, in which 94.5 and 97.5% of the attachments where successful (Gygax et al. 2007).

Since 2009 a 16 bail robotic rotary (RR; DeLaval automatic milking rotary–AMR™, Tumba, Sweden) has been co-developed and tested at the Elizabeth Macarthur Agricultural Institute site (EMAI, Camden, NSW, Australia). The RR is expected to be capable of carrying out in the order of 50 cow milkings per hour with the installation of two robots (Figure 4.1): a teat preparation robot (teat preparation module; TPM), and a teat cup attachment robot (automatic cup attacher; ACA). The RR achieves such high levels of throughput (compared to a single-box robot)

[2] Commission directive 89/362/eec of 26 May 1989 on general conditions of hygiene in milk production holdings 1989: Official Journal L pp. 0030 - 0032.

through the design which leaves the robotic devices (TPM and ACA) based in a fixed location whilst the rotary platform rotates the cows around from the entry point to the exit point in a stop-start operation. Figure 4.1 shows a schematic overview of the 16 bail RR with the entry to the rotary, the TPM, the ACA and the exit from the rotary. Commercial installations of the RR will have 24 bails (compared to the 16 bail prototype) and will have the option to achieve an even higher throughput, (in the order of 90 cow milkings per hour) with the installation of four robots (two TPM's and two ACA's). With either installation (2 or 4 robots) an additional robot (teat spray module; TPM) can be installed prior to the exit for post-milking teat sanitation.

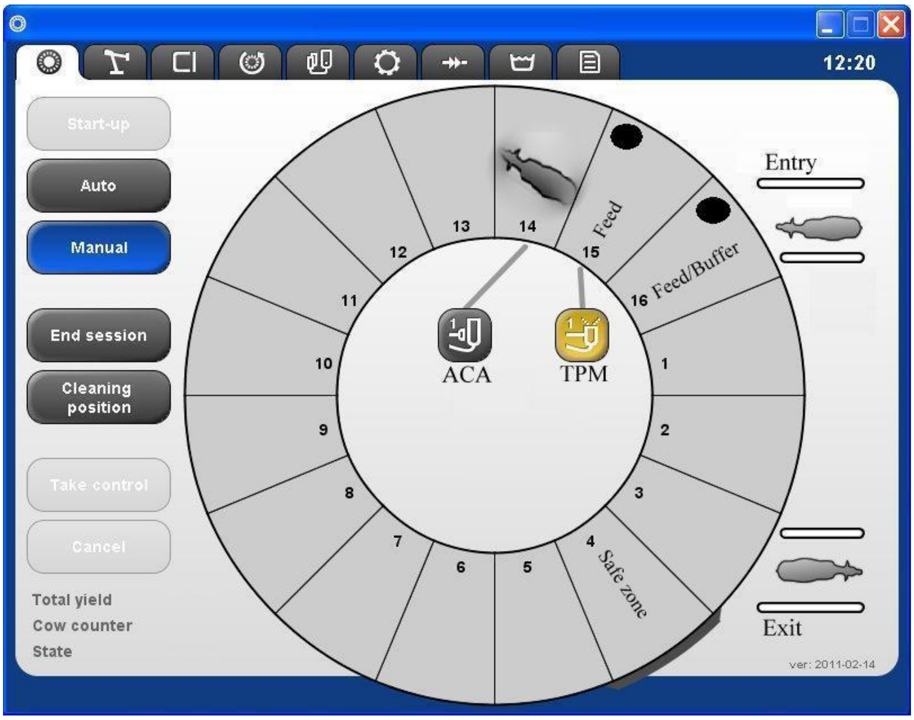

Figure 4.1: Schematic of the RR showing; the entry to the rotary, teat preparation module (TPM, in yellow), automatic cup attacher (ACA, in grey), exit from the rotary platform, safe zone (bar shown at the side of bail 4) and the feed available at the TPM and buffer bail positions (bails 15 and 16, feed bin position indicated as black circles; schematic graphic user interface of AMR™; courtesy of DeLaval)

The first commercially released version of the RR is a 24 bail herringbone rotary (HBR™, DeLaval) with the option of two to five robots. The purchase and installation of one or more TPM will not be compulsory, which may create an opportunity for the farmer to reduce the cost of the capital infrastructure by choosing not to install a TPM. The TPM functions are 3-fold: to clean teats in preparation for milking to reduce bacterial contamination of the milk (Knappstein et al. 2004); to stimulate the OT release and the milk let down process, initiating milking (Macuhová and Bruckmaier 2000); and to remove and discard the foremilk. It is not unrealistic to expect that in Australia, and in other countries where premilking preparation prior to teat cup attachment is not a mandatory requirement, farmers may opt to not purchase a TPM. Whilst the study of Jago et al. (2006a) with single-box AMS showed no difference in attachment success between two treatments (with or without premilking stimulation and cleaning), it cannot be assumed that the same results will be achieved with the RR. Investigation into the effect of premilking teat preparation on the system performance, in terms of attachment success and milk harvesting efficiency was conducted and is reported here to ensure that informed decisions can be made regarding the installation (or lack) of TPM within the RR.

This study focuses on the effects of not using a TPM in a prototype RR on attachment accuracy and milk removal characteristics of individual cows. It was hypothesised that using the TPM will result in a higher attachment accuracy, in terms of attachment success and attachment speed (time needed for attachment of four teat cups) and will increase milk flow, thereby lowering the cups-on time and improving the potential and actual throughput and milk harvesting efficiency of the RR.

4.3. Materials and methods

4.3.1 Experimental design

During the trial 180 (range 163–193) mixed breed (majority Holstein-Frisian and approximately 10–15% Illawarra) cows were managed and grazed as per recommended practice (Kerrisk 2010), as a single voluntarily trafficking herd and milked with a prototype RR, at the EMAI site (Camden, NSW, Australia). During the trial the herd averaged 22.7 kg daily milk production (median 21.6; SD 8.7 kg), 170 days in milk (median 167; SD 115 d) and had an average parity of 2.7 (range 1–11; median 2; SD 1.8).

Cows accessed a ‘day’ pasture break from 0900 to 1900 h and a night pasture break from 1900 to 0900 h. The total feed allocation target of 21 kg DM/cow per day included 4.5 kg concentrates consumed through automatic concentrate feeders located in the post-milking feeding area. Cows were given an additional small allocation of pelleted concentrate in the first two bails of the RR to encourage voluntary cow traffic onto the platform (~0.3 kg/visit).

The RR was available for cow access for 24 h per day (except during system washes between approximately 0700–0800 h and 1800–1900 h). Cows voluntarily moved around the system, from the paddocks to the RR, passing a set of automatic drafting gates (smart selection gates; SSG; DeLaval, Tumba, Sweden) where they were drafted based on whether milking permission was granted or denied. Milking permission was granted when the interval since the previous milking exceeded 4 h or the previous milking was incomplete (< 50% of expected yield harvested from one or more quarters, one consecutive time only). Cows were drafted to a pre-milking holding yard (188.5m^2) when milking permission was granted and back to pasture when milking permission was denied. After exiting the RR platform the cows had access to four automatic concentrate feeders where they received an individualised allocation of pelleted concentrates.

The study was carried out across two periods of five consecutive experimental days in October and November 2011. To test the effect of premilking teat preparation, preformed by the TPM, two treatments were tested; **wash** and **no wash** (**NW**). Each day of the trial was split into four periods (0000–0600 h; 0600–1200 h; 1200–1800 h and 1800–0000 h) and treatments were randomly assigned across the days (with two wash and two NW treatments in each 24 h period; Table 4.1). Washing was conducted with a separate, 'teat-cup-like', cleaning device. The water temperature measured was approximately 18°C. The washing regime used, as referred to by DelPro (DeLaval AMR™ management support software), was a light program, resulting in a target cleaning teat contact time of 5.5 s/teat. The average cleaning operation time was 80.1 s per cow (median 74.0; SD 27.2 s), including teat location and teat contact time. During the wash treatment, the average time from the end of cleaning to the attachment of the first teat cup was 80.5 s (median 65.0; SD 50.3 s).

Table 4.1: Trial design with no wash and washing treatments randomly assigned across time periods of the day

Period	Date	Time			
		00–06 h	06–12 h	12–18 h	18–00 h
1					
	16/10	-	-	NW	Wash
	17/10	NW	Wash	NW	Wash
	18/10	NW	Wash	Wash	NW
	19/10	Wash	NW	NW	Wash
	20/10	Wash	Wash	NW	NW
	21/10	NW	Wash	-	-
2					
	31/10	-	-	NW	NW
	1/11	NW	Wash	NW	Wash
	2/11	Wash	NW	Wash	NW
	3/11	NW	Wash	Wash	NW
	4/11	Wash	Wash	NW	NW
	5/11	Wash	Wash	-	-

NW = no teat wash, Wash = teats cleaned prior to being milked

4.3.2 Statistical analyses

4.3.2.1 Outcome variables

Treatment impacts were measured on: (1) the effect of premilking teat preparation by the TPM on attachment success rate of individual teat cups (left back = LB; right back = RB; left front = LF; and right front = RF); (2) the effect of premilking teat preparation on the speed of attachment of the milking teat cups; and (3) the effect of premilking teat preparation on milk harvesting efficiency, measured as: (a) the average milk flow rate; and (b) the peak milk flow rate (both in kg/min). Attachment accuracy and milk flow rates were electronically collected through the RR support software, DelPro. An *ad hoc* custom-made software program, which logged and date/time stamped all the robot actions, was used for electronic collection of robot action data. These robot action time stamps were used to accurately calculate the cleaning and attachment times of the TPM and ACA. Since unmilked quarters cannot have an average or peak milk flow rate all cows with one or more unmilked quarters were deleted from the dataset for the flow rate analyses.

4.3.2.2 Explanatory variables

Data generated were collected and exported electronically through DelPro. These data included the major explanatory variable wash treatment in addition to: interval between previous milking and the observed milking session (MI; hours), average daily milk production level per cow (7-day average production; kg), stage of lactation (days in milk; DIM) and parity (lactation number) to investigate the association with the outcome variables.

4.3.2.3 Statistical models

Data were analysed with GenStat 13th Edition (VSN International, Hertfordshire, UK). Binary data were analysed with a generalised linear mixed model (GLMM) to test the association of treatment (NW vs. wash) and other electronically collected variables (MI, DIM and parity) with the outcome variable; (1) proportion of successfully attached teats. Period, animal, and their interaction, milk-point on the platform of the RR (MP), and the MP × period interaction were used as random effects in the model (period + animal + period.animal + MP + MP.period).

Linear mixed models (fitted using a REML procedure) were used to test the association of treatment (NW vs. wash) and other explanatory variables with the numerical outcome variables; (2) attachment speed, (3a) average milk flow rate and (3b) peak milk flow rate. Similar explanatory variables (MI, DIM, 7 d production and parity) and random terms (period + animal + period.animal + MP + MP.period) were used as described above. Model assumptions of normality and equal variance were evaluated, and if invalid, the outcome variables were transformed to meet the assumptions. Observations with residuals greater than four standardised standard deviations were deleted for the analysis of the effect on the average and peak milk flow rates to make the assumption of normal and equal variance of the residuals valid. Attachment speed data were log transformed as the raw data did not meet the assumption of normality.

The assumption of linearity for the explanatory variables described above, with the outcome variable was tested in both the GLMM model and REML models, using restricted cubic splines. Categorised variables were used for further analyses when this assumption was invalid. All variables with a P-value < 0.25 in univariable analyses were included in the multivariable models. Non significant variables (P-values > 0.05) were then eliminated using a backward stepwise approach. Odds ratios and their confidence limits from the final binary model, and predicted means of the linear mixed models are presented and discussed.

4.4. Results

4.4.1 Descriptive results

During the 10 day experimental data collection period 2574 milkings were recorded. During the NW treatment 1373 milkings were conducted, while the wash treatment was applied during 1174 milkings. In the NW treatment 558 cows exited the RR platform with one or more teats unmilked compared to 406 cows during the wash treatment. On average, the attachment time was 79.6 s per cow and the average operation time per visit of the TPM was 80.1 s (included teat location and teat contact washing time). The average milk yield per milking was 11.5 kg/cow with an average mean milk flow of 2.3 and average peak milk flow of 4.3 kg/min.

4.4.2 Attachment success rate

Milking interval was categorised and grouped in four quartiles before analysis. After backwards elimination of non significant explanatory variables (parity and DIM), the final GLMM model is shown in Table 4.2. Using the washing treatment resulted in a 1.5 times higher odds of having individual teats successfully attached for milking. Individual quarters significantly affected attachment success, as the RF teat had 3 times higher odds of successful attachment compared to the LB teat. Cows milked with a MI < 8.14 hours had 2.16 times lower odds of having a quarter attached successfully compared to those with longer milking intervals. There was also a trend found between treatment and the individual quarters on the proportion of successful attachments (Figure 4.2), however, this interaction (treatment × quarter) was not significant (P = 0.068). The LB and RB teats were the least likely to be successfully attached. The RF teat had 3.1 times greater odds of being successfully attached compared to the LB teat (in the NW treatment). Attachment success rate of the back quarters tended to increase when exposed to the wash treatment as the ACA had 1.5 and 1.6 times higher odds of attachment for a LB and RB teat respectively compared to attachment success rate in the NW treatment.

Table 4.2: Final generalised linear mixed model to investigate the association of treatment and other explanatory variables with the outcome variable–probability of a successful attachment of individual quarters. Period, animal and their interaction, milking point and milking point × period interactions were included as random effects

Effect	Categories	Parameter estimate	Standard Error	Odds (95% CI^)	P-value
Intercept		0.87	0.19		
Treatment					<0.001
	No wash	0.00			
	Wash	0.42	0.11	1.51 (1.22, 1.88)	
Quarter					<0.001
	LB	0.00			
	RB	0.27	0.12	1.31 (1.05, 1.65)	
	LF	0.72	0.12	2.06 (1.64, 2.58)	
	RF	1.13	0.12	3.10 (2.47, 3.88)	
Milking interval (h)					<0.001
	≤8.14	0			
	8.15–12.94	0.51	0.09	1.66 (1.35, 1.99)	
	12.95–19.68	0.77	0.09	2.16 (1.80, 2.59)	
	≥19.69	0.63	0.09	1.88 (1.57, 2.26)	
Treatment × Quarter					0.068
	Wash × LF	-0.32	0.17	0.73 (0.52, 1.01)	

^Confidence interval
(LB = left back, RB = right back, LF = left front and RF = right front quarters)

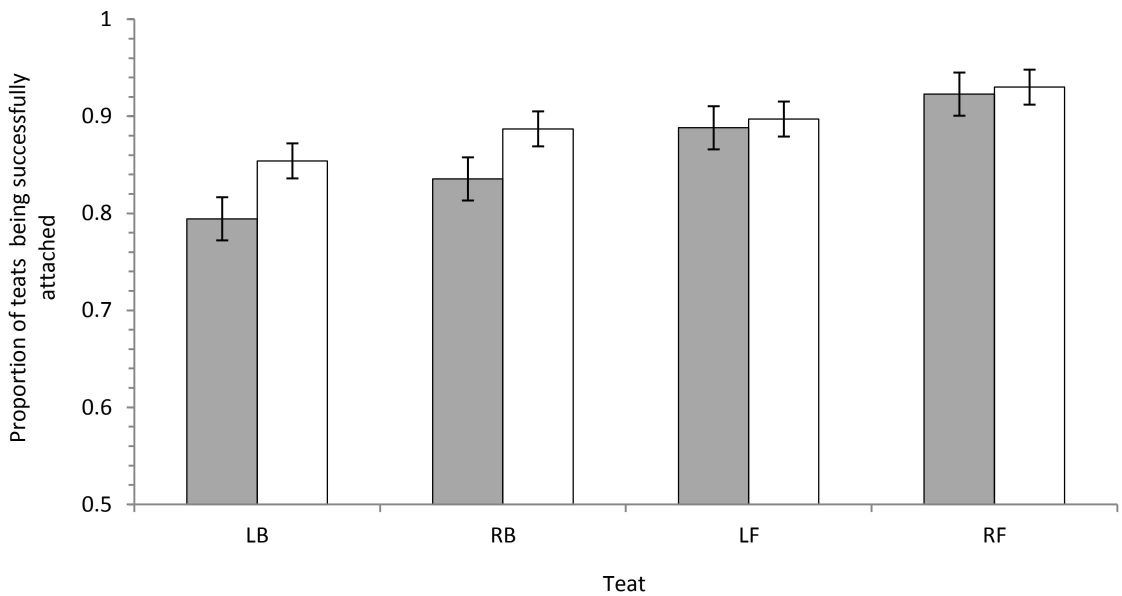

Figure 4.2: Predicted means; successful attachments of individual quarters exposed to no wash (grey bars) and wash (white bars) treatments at individual quarter level (LB = left back, RB = right back, LF = left front and RF = right front). Vertical bars indicate SEM (standard error of the mean)

4.4.3 Attachment time

As the variables parity and MI were unable to meet the assumption of linearity, they were categorised in quartiles. The final model is shown in Table 4.3 indicating the significant effects of treatment, parity and MI on attachment time. Milking cup attachment speed was 4.3 s faster for cows exposed to the washing treatment before being rotated to the ACA bail compared to attachments occurring with the no-wash treatment. Cup attachment was significantly faster for third lactation cows compared to cows in lactation 1 and ≥ 4 (67.8, 77.6 and 74.3 s/attachment respectively) and for second lactation cows compared to cows in lactation 1 (72.0 and 77.6 s/attachment respectively). Cows with a MI between 12.95–19.68 h had significantly faster cup attachment (71.1 s) than cows with MI's ≤ 8.14 h (74.7 s).

Table 4.3: Final linear mixed model to investigate the association of treatment and other explanatory variables with the outcome variable–attachment time (estimates shown as log transformed effects, with back transformed predicted means in brackets). Period, animal and their interaction, milking point and milking point × period interactions were included as random effects

Effect	Parameter	Estimate	Standard Error	95% CI^ Lower	95% CI^ Upper	P-value
Intercept		4.41 (72.8)	0.05			
Treatment						<0.001
	No wash	0.00 (75.0)				
	Wash	-0.06 (70.7)	0.01	-0.08	-0.03	
Parity						0.033
	1	0.00 (77.6)				
	2	-0.08 (72.0)	0.04	-0.16	0.01	
	3	-0.13 (67.8)	0.04	-0.22	-0.05	
	≥4	-0.04 (74.3)	0.04	-0.13	0.04	
Milking interval (h)						0.044
	≤8.14	0.00 (74.7)				
	8.15–12.94	-0.03 (72.2)	0.02	-0.07	0.00	
	12.95–19.68	-0.05 (71.1)	0.02	-0.09	-0.01	
	≥19.69	-0.02 (73.5)	0.02	-0.05	0.02	

^Confidence interval

4.4.4 Milk flow rates

4.4.4.1 Average milk flow

No significant treatment effect was found on the average milk flow per cow (Table 4.4). As the average 7-d milk production, MI, and DIM did not meet the assumption of linearity, they were grouped and categorised in quartiles. Production level significantly affected milk flow. In addition a significant interaction between the explanatory variables MI and DIM was found (Table 4.4 and Figure 4.3).

Table 4.4: Final linear mixed model to investigate the association of wash treatment and other explanatory variables with the outcome variable–the average milk flow rate (kg/min). Period, animal and their interaction, milking point and milking point × period interactions were included as random effects

Effect	Parameter	Estimate	Standard Error	95% CI^ Lower	95% CI^ Upper	P-value
Treatment						0.16
	No wash	2.59				
	Wash	2.63	0.03	2.58	2.68	
Production						<0.001
	<15.2	2.36				
	15.2–21.58	2.53	0.08	2.38	2.68	
	21.59–28.5	2.73	0.08	2.58	2.88	
	>28.5	2.81	0.08	2.66	2.96	
Milking interval (h)						<0.001
	≤8.14	1.73				
	8.15–12.94	2.61	0.04	2.52	2.69	
	12.95–19.68	2.95	0.04	2.86	3.03	
	≥19.69	3.16	0.04	3.08	3.24	
Days in Milk (d)						<0.001
	<76	2.73				
	76–166	2.74	0.11	2.53	2.94	
	167–241	2.63	0.11	2.43	2.84	
	>242	2.34	0.11	2.13	2.54	
DIM × MI						
	76–166 × ≥19.69	3.29	0.12	3.05	3.52	<0.001

^Confidence interval
DIM = days in milk, MI = milking interval

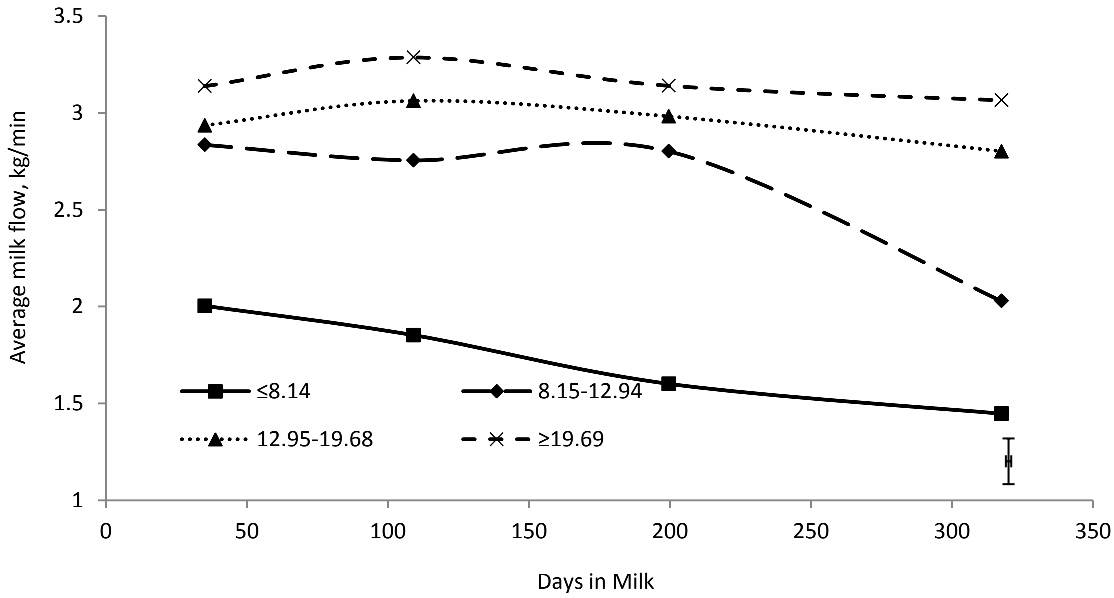

Figure 4.3: Average milk flow (kg/min.cow) in relation to the stage of lactation (DIM) and the interval between milkings; in hours. Vertical bar indicates SEM (standard error of the mean)

4.4.4.2 Peak milk flow

After backwards elimination of non significant explanatory variables a significant interaction was found between treatment and MI on the peak milk flow (Table 4.5). Cows exposed to the wash treatment with a MI ≤ 8.14 h had a significant higher peak flow rate compared to cows in the NW treatment with the same MI.

Table 4.5: Peak milk flow (kg/min) during milking after teat cup attachment in relation to the wash treatment (NW vs. wash) and milking interval (h)

Treatment	Milking interval (h)			
	≤8.14	8.15–12.94	12.95–19.68	≥19.69
No wash	3.93 ± 0.05^{Aa}	4.79 ± 0.07^{b}	5.02 ± 0.06^{c}	5.26 ± 0.05^{d}
Wash	4.25 ± 0.05^{Ba}	4.83 ± 0.07^{b}	5.07 ± 0.06^{c}	5.30 ± 0.06^{d}

^{a,b,c,d} Means within line without common lowercase superscript letter are significantly different (P < 0.05)
^{A,B} Means within column without common uppercase superscript letter are significantly different (P < 0.05)
Values shown as predicted means and ± S.E.M

4.5. Discussion

As the novel prototype RR is the first high throughput AMS in the world it is extremely important to investigate the effect of premilking teat preparation on teat cup attachment success, speed and milking speed. There was a significant treatment effect on the success of teat cup attachment by the ACA. The ACA had a 1.5 times higher odds of successful attachment of a teat when the cow was exposed to the wash treatment prior to being rotated to the ACA attachment bail. This result is in disagreement with the finding of a previous study carried out by Jago et al. (2006a). In that study, no significant effect on attachment success between brushing and no brushing of teats before milking, was found. However, that study was carried out with a single-box AMS in which the attachment success rates were higher, compared to the prototype RR used in this study. As the results presented here were generated with a prototype RR, we should expect technological improvements to result in improved attachment success in commercial versions of the product. Software and hardware upgrades conducted since the reported study has already resulted in significant improvements to the attachment success even with the prototype RR.

It was shown in the presented study that front quarters were significantly more likely to be attached successfully, having 3.1 times higher odds for RF compared to LB quarters. Previous studies conducted with single-box AMS have also shown (albeit not quantified) differences in attachment success between front and back quarters (Capelletti et al. 2004; Hamann et al. 2004). In agreement with the findings presented in this study it has been shown that back quarters were more difficult to attach for an automatic cup attachment robot. A milking interval between 12.95–19.68 h had 2.2 times higher odds of being attached successfully compared to cows with a MI ≤ 8.14 h. A study of Bruckmaier and Hilger (2001) showed the relation between MI and milk ejection, in where a MI < 8 h would result in a lag time in the milk let down process, indicating the effect of degree of udder filling. Whilst an udder fill effect was likely in the current study, it is also likely that some of the cows with a MI ≤ 8.14 h were previously incompletely milked, and thus were sent back to the system for a second attempt at milking. These incompletely milked cows could have a more challenging udder conformation, as only one or more quarters were incomplete, resulting in a lower proportion of successful attachments at the second attempt. For the purpose of this study an unsuccessful milking was defined as a milking whereby one or more teats cups were not attached; however cows not completely milked (e.g. due to premature cup removal) were also milked at a second attempt. The effect of these cows milked for a second attempt was however not classified in this study. It was interesting to note that there was a trend shown by the interaction between treatment and individual quarters on the proportion of successful attachments. The trend in attachment success showed that the back quarters had an increased likelihood of being attached after receiving a wash treatment, as they had a 1.5 and 1.6 times higher odds of a successful attachment (LB and RB quarter respectively). However whilst this interaction was not significant at α 0.05 level, it is valuable to note that the attachment success of the back quarters did tend to be influenced by the wash treatment. This result could be explained by the fact that, as soon as the first teat cup is attached, the milk let down system is stimulated and OT is released. Stimulation of only one teat is shown to be sufficient to induce the milk let down process and maintain a sufficient OT level (Bruckmaier and Hilger 2001), therefore a smaller effect of washing may have been created for the front teats as these teats were attached after the back teats. The effects of premilking teat preparation on attachment success rate in the prototype RR shows that careful consideration should be taken when deciding whether or not to invest in a TPM, as the attachment accuracy can be significantly influenced by the deactivation of the TPM.

It was shown in this study that the attachment time per cow was significantly affected by the wash treatment. A cow with teats cleaned before entering the ACA bail had teat cups attached 4.3 seconds faster than cows in the no-wash treatment. Attachment speed in a high throughput AMS (such as the RR) is of even higher importance compared to the single-box AMS technology. With the RR the robotic devices do not have to wait until a cow is finished milking, but instead cows are continually being rotated towards the robots for attachment, the time taken to clean teats and attach cups will be the limiting factor for system throughput. Studies have been conducted with single- and multi-box AMS to address the increased throughput when time savings are realised. It is known that the time used for the different system operations, such as premilking teat preparation, cup attachment, milking time of the cow and post-milking activities will influence the capacity of the single- and multi-box AMS (Sonck and Donkers 1995; Jago et al. 2006a; Gygax et al. 2007; Davis et al. 2008a). An increase of 30 seconds per AMS milking will result in a milking capacity reduction of five to eight percent per day (de Koning and Ouweltjes 2000). If the assumption is made that the RR in this study is not limited by cows voluntarily moving around the system and entering the platform, with attachment times of 75 s (NW treatment) plus 5 seconds per rotation/cow, the RR has the potential to milk 45 cows per hour (3600 s/80 s). With an attachment time of 70 seconds (+5 s rotation time) 48 cows can be milked per hour, which is a 7% increase in capacity per hour. In other words, when the system is available for 18 h per day (accounting for some idle time and system cleanings), the potential would exist for an additional 54 milkings to be conducted daily with the TPM activated. Whilst an early study with single- and multi-box AMS reported attachment times of two minutes (Frost et al. 1993), more recent studies have demonstrated an improved performance, with attachment speeds ranging from 53 to 97 seconds for different systems (Dzidic et al. 2004; Luther et al. 2004; Christoph 2004; Macuhová et al. 2004). While the RR used in this study is a prototype; world's first high throughput system, it is expected that with technology improvements the attachment time of 73 s will decrease. It is also important to note, that when four robots are in use (two TPMs and two ACAs) each robotic device only has to clean or attach two teats, reducing the device handling time per cow resulting in further increases in throughput potential.

Whilst cows milked with a MI between 12.95–19.68 h were more likely to be have successful teat cup attachment compared to cows milked with a MI ≤ 8.14 h, the attachment speed of this MI group was also significant faster compared to the ≤ 8.14 h MI group. This was most likely caused (at least in part) by the level of udder filling, whereby a higher MI is associated with a fuller and more distended udder which likely increases the ease for any automatic cup attachment device to locate the teats.

The effects of parity reported here may be explained by changes in udder conformation and the more difficult shaped (compact and higher) udders often associated with younger cows. The behaviour of the younger animals could also have affected the teat cup attachment times. Differences in attachment performance for different udder shapes has also been reported in previous AMS studies (Migliorati et al. 2004).

Whilst the average milk flows were not significantly affected by treatment, there was a significant interaction found between treatment and MI on the peak milk flow. Peak milk flow was significantly higher for cows with a MI ≤ 8.14 h when teats were cleaned before milking. This could indicate again the relationship between the level of udder filling described before (Bruckmaier and Hilger 2001), showing a lag time from udder stimulation and milk let down for cows with a smaller MI. However, the time delay between last teat cleaned and first cup attached averaged 1 min and 20 s, which is deemed sufficient to induce the milk let down process (Macuhová et al. 2004). The fact that, as discussed before, the MI group ≤ 8.14 h included cows milked at a second attempt after a previous incomplete milking could have influenced the milk harvesting result in this study. There was no difference found between the NW and wash treatment for other MI categories on milking characteristics. The milk flow rates reported here were similar to milk flow rates reported in the literature (Sandrucci et al. 2007; de Koning 2011b; Hogeveen et al. 2001).

It is acknowledged that this study did not investigate the impact of either treatment on udder health or the bulk milk quality. This was predominantly due to the short duration of the study and that all milk (regardless of the treatment) was collected in the same milk vat.

Whilst the results presented here indicate a significant advantage in teat cup attachment (accuracy and speed) and milk harvesting rates, further research will be necessary to determine the impact on udder health and milk quality. As only a small number of conventional farms conduct premilking teat preparation regimes in Australia, some of these farmers might not recognize the need for a TPM when purchasing a RR. Of the farms that do conduct premilking teat preparation the majority (78%) conduct only strategic washing, i.e. cleaning only visibly dirty teats before cup attachment (Davis et al. 2008a). The TPM technology however is not able to visually determine whether or not teats are dirty. When the decision is being made by farmers not to install a TPM, no solution will be available in periods when there is a higher need for teat cleaning due to seasonal and environmental conditions. Farmers choosing not to install TPM(s) will need to consider alternate solutions to cope with dirty teats thereby ensuring that udder health and milk quality are not compromised. An udder preparation system outside the RR, as previously described by Davis et al. (2008b), could be an option. A cleaning system containing in-floor jetting sprayers in the concrete holding areas spraying and washing the underside of the cows' udder in the first of two holding areas, allowing time for drip drying before teat cup attachment could be a possibility. However such a system does not target individual teats and will not be as accurate as the sophisticated 'teat-cup-like' cleaning device used in this study. Undoubtedly, based on the results of the work presented here, such a system will have a negative impact on milk harvesting success and speed when compared to operation with the installation of a TPM.

4.6. Conclusions

It was found that the attachment success and attachment time was significantly influenced when no premilking teat washing procedure was in place. This meant that the ACA was more able to accurately attach teat cups after a cow was exposed to a teat wash treatment. Premilking teat preparation did not result in an increased average milk flow, however a positive impact was reported on the peak milk flow. These findings indicate that careful consideration by farmers into the decision of whether or not to invest in a TPM is necessary. The results presented here, generated with a novel prototype RR, the DeLaval AMR™, can support the decision making process of farmers on whether or not to install and use a TPM in RR installations. The RR is due for commercialisation in 2012 and there is currently no published literature pertaining to any aspect of the affect of cleaning teats on the attachment success rates and milk removal from the gland with the RR indicating that the findings presented here are invaluable to furthering industry understanding with this new milk harvesting technology. This study was not designed to investigate the effects of washing vs. no washing on udder health or milk quality but these are also very important considerations that should contribute to the decision making process. As the development of the technology continues prior to full commercialisation of the product, improved performance and attachment accuracy will undoubtedly result. However, it is anticipated that the trends and treatment differences indentified in this study will likely remain unchanged. The relationship between premilking teat preparation and attachment accuracy should create awareness of the importance of teat cleaning within the RR. Moreover, whilst there are other solutions available to farmers for premilking teat preparation, commissioning a RR without a TPM equipped would negatively impact on the potential throughput of a well utilised system.

4.7. Acknowledgements

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Chapter 5. Attachment accuracy of a novel prototype robotic rotary and investigation of two management strategies for incomplete milked quarters

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Overview of Chapter 5

Failures in attachment necessarily result in increased rate of incomplete milkings. Incompletely milked cows in turn need to be returned to the robotic rotary (RR) to avoid milk yield reduction and increase health risks, lowering the operational efficiency. Chapter 4 demonstrated that teat cup attachment rate of RR can be increased by use of teat preparation module (TPM). However rate of attachment was still lower than desirable. As a result of this finding, potential management strategies for incompletely milked cows and their implications on dairy layouts were investigated.

Chapter 5 details the results of an investigation into two different management strategies of incompletely milked cows. The relationship between management decisions (feeding cows on a feedpad pre- or post-milking) and attachment success rates after a previous incomplete milking may help to determine different management strategies for famers to increase the success rate of milking after two attempts.

Attachment accuracy of a novel prototype robotic rotary and investigation of two management strategies for incomplete milked quarters

5.1. Abstract.

Throughout 2009 and 2010, FutureDairy (Camden, NSW, Australia) was involved in testing a novel prototype robotic rotary (RR). The RR is capable of carrying out 50 milkings per hour. To achieve the high throughput the rotary rotates the cow to the cup attachment robot and then around the platform. The robot does not remain with the cow during the entire milking process. When not all teat cups are attached during a milking session there is an opportunity for cows to be sent back to the waiting yard for a second milking attempt. The study presented here was designed to test whether or not the extension of the interval to a second milking attempt improved milking success of incompletely milked cows. It was expected that with a lower milking interval between the two subsequent milkings the changes to the udder conformation could negatively affect the attachment success at the second attempt. The one hour milking interval treatment (**RR 1 h**) simulated cows being drafted directly back to the pre-milking waiting yard, whilst the three hour milking interval treatment (**RR 3 h**) was designed to simulate cows being drafted back after accessing post-milking supplementary feed on a feed pad. The RR data are reported alongside similar historical AMS data that were collected electronically over a four-week period during March and April 2008 to provide a benchmark of attachment performance under similar conditions from milkings conducted with single-box AMS units. The results presented in this chapter showed no significant difference between the frequencies of successful attachment in the second attempt between the **RR 1 h** and **RR 3 h** treatments indicating that a reasonable level of flexibility exists with management of incompletely milked cows and dairy layout designs. Milk production level affected the probability of success at second attempt, which was about 7.5 times higher in cows with an average milk production level greater than 19.3 kg than those with less than 10.8 kg. When looking at the total proportion of cows successful milked after two attempts, it was found that successful milking was more likely in multiparous cows compared to primiparous cows. The historical AMS data showed that success rate at second attempt significantly increased with increase in daily milk yield and with increase in milking interval.

Additional keywords: success-rate, pasture-based, automatic milking system, robotic rotary, dairy

5.2. Introduction

Whilst automatic milking system (AMS) technology was initially designed for small family farms, more recently (after continuous technological advancement and an increased level of AMS management skills and confidence in the technology) larger farms with more than 500 cows are adopting the system (Svennersten-Sjaunja and Pettersson 2008). Milk yield, milking frequency, inter-milking interval, teat-cup attachment success rate, and length of the milking procedure are important functional efficiency aspects of any AMS (Gygax et al. 2007). When a teat cup is not attached to an intended teat, the cow can leave the AMS unmilked in that quarter. A study with an average attachment failure rate of 7.6% showed that, when accounting for the effect of an extended milking interval (of the unmilked quarter), milk production for the affected quarter was 26% lower than the yield measured after milking sessions associated with successful teat cup attachment (Bach and Busto 2005). This impact on yield and the additional impact on system efficiency and udder health, indicate the importance of accurate attachment. Studies around existing indoor AMS have also shown the importance of the design of the automatic milking farm/barn to improve system efficiency, which has importance with regard to both economic and animal welfare needs (Halachmi et al. 2003; Halachmi 2004).

During 2009 and 2010, a novel prototype robotic rotary (RR; DeLaval automatic milking rotary–AMR™, Tumba, Sweden) was co-developed, installed, and tested at the Elizabeth Macarthur Agricultural Institute (EMAI), Camden, NSW, Australia. The RR is the world's first reported high throughput AMS to be developed. It is expected to be capable of carrying out up to 900 or 1600 milkings per day depending on the installation (with either two or four robots respectively) and system management.

The equipment used is a prototype internal, 16 bail, herringbone rotary (DeLaval HBR). To enable the RR to achieve such high levels of throughput (compared to a single-box robot) the robotic arms remain stationary whilst the rotary platform rotates the cow around from the entry point to the exit point in a stop-start operation. The fact that the robotic arm does not remain with the cow during the entire milking process means that any prematurely removed and unattached milking cups cannot be (re)attached once the cow has passed the attachment bail (see Chapter 2 for a more detailed explanation of equipment functioning). The configuration of the RR platform is such that cows are positioned at approximately 120° to the robotic arm (the angle of the cow on the platform is 30°). This is a significant change in orientation compared to the positioning in a single-box robot. All existing commercial AMS units have a robot approaching the side of the cow from a 90° angle or from behind. The combined effect of no opportunity for reattachment and cow orientation in relation to the robotic arm, increases the potential occurrence of incompletely milked cows.

Whilst investigating the feasibility and application of the RR, assessments of the reliability of the RR itself and development of practical working routines is necessary. One particular area of interest is the most suitable management routines for cows which have an “incomplete” milking session. For the purposes of this study an “incomplete” milking is defined as a milking whereby not all teats are attached successfully for milking. When a given milking session is defined as incomplete, there is an opportunity for cows to be granted a second milking attempt. If the appropriate infrastructure exists, the incomplete cow can be drafted directly back to the waiting area for another milking. In a pasture-based system it is not uncommon to have a feedpad for provision of supplementary feed within close vicinity of the dairy. Where such a facility exists there may also be an opportunity to draft cows to the feeding area to extend the interval between the first and second attempt at milking. The subsequent success rate of reattachment in these two different situations may differ as a direct result of the interval between the two milking sessions (1st and 2nd attempt) due to the impact of interval on the udder and teat conformation. It is known that longer milking intervals between two attempts are associated with a higher level of udder fill (Knight et al. 1994 and Stelwagen et al. 1996) and therefore a change in the likelihood of successful attachment could be expected.

This study was conducted to evaluate success rate of reattachment after an incomplete milking with two management strategies. It was hypothesised that the extension of the interval between two attempts for milking increases the attachment success rate of previously incompletely milked cows. It was expected that with a shorter milking interval between the two milking attempts, attachment of milking cup(s) to the unmilked teat(s) would be more challenging due to the increased flaccidity and proximity of the teats. The results of this investigation should allow a more informed approach to be taken in proposing suitable management routines and dairy layouts for commercial RR installations.

Given the lack of similar data reported in the literature and that the AMS is commercially available (and widely adopted globally), in addition to the above objectives historical data collected electronically was analysed and presented to provide a benchmark of attachment performance under similar conditions from milkings conducted with single-box AMS units at the same experimental site. An additional objective of the study was to quantify and report any trends in attachment success on individual quarters.

5.3. Materials and methods

5.3.1 Experimental design robotic rotary dairy

During the four-day trial (May 24–27, 2010) the 155 mixed breed (majority Holstein-Frisian and approximately 10–15% Illawarra) cows were managed and grazed as per recommended practice (Kerrisk 2010) at Elizabeth Macarthur Agricultural Institute (Camden, NSW, Australia). At the time of the study the cows averaged 174 days in milk (DIM; median = 174), 3.2 lactations (median = 3), and were producing 10 kg milk per milking and 17.5 kg milk per day (7-day average production levels). Each day the herd was allocated two accurate (12 h) allocations of feed, one of pasture and one of partial mixed ration (PMR) due to the limited availability of pasture at the time of the trial. The PMR was made available each night on a sacrifice feeding area while the pasture allocation was available during the day. Average feed intake (kg DM/cow per day) during the study period was 8.6 pasture (measured through pre- and post-grazing of all grazed paddocks) and 12.1 PMR (7 kg DM maize silage, 2.5 kg DM Lucerne hay mix and 2.6 kg pelleted concentrates; measured through electronic scale in a mixer wagon). In addition, a small amount of pelleted concentrate (~250 g) was made available in the RR to entice voluntary cow traffic through the system and encourage correct positioning of the cows at the entry bail. During the trial, cows had voluntary access to two adjacent single AMS stalls in the afternoon and night (1400 to 0700 h) and were drafted to the RR in the morning (0700 to 1200 h) for the completion of the RR experimental milking sessions (0800 to 1400 h). Each day approximately 100 cows were milked during the observed milking session; these were not necessarily the same 100 cows each day but 92% of cows had three or more observed milkings and 57% of cows were involved in all four observation sessions (n = 129 different cows recorded during the four-day period).

For the purpose of this study the first observed milkings will be called **first attempt** and any cows that did not have all cups successfully attached at the first attempt will be called **incomplete**; conversely, if all cups were attached the milking is termed **complete**. Normally premature teat cup removal resulting in a low milk yield for any individual quarter would also be classed as an incomplete milking but in this study such cases were avoided by manual intervention to ensure that only completely unmilked teats were contributing to the incomplete records.

All incompletely milked cows at the first milking attempt were returned for a **second attempt** after either **one hour (RR 1 h)** or **three hour (RR 3 h)** waiting periods. During the second attempt the RR (automatically) targeted only the quarter(s) that was/were missed at the first attachment attempt. In other words, quarters milked successfully ("complete quarters") at the first attempt were not remilked at the second attempt. On days 1 and 2, cows were subjected to the **RR 1 h** treatment. A total of 212 milkings were observed during the milking sessions over these two days. Cows were milked in batches of approximately 50 cows at a time to allow staff to return incomplete cows (n = 40 over two day period) back to the system within an hour, simulating an automatic drafting system that could generate a similar result with voluntary cow traffic. On days 3 and 4 cows were subjected to the **RR 3 h** treatment with all cows (216 milkings) receiving their first milking in one batch. The incomplete cows (46 milkings) were drafted to the sacrifice feeding area (otherwise only available at night) to allow them to eat and loaf during their three hour waiting period between first and second attempt. These cows were then returned from the feeding area to the waiting yard at around three hours after milking (minimum milking interval two hours). This treatment was designed to simulate the situation where cows gain access to a feeding area before being drafted back to the waiting yard as they exited the feeding area. To minimize any negative impact on animal welfare, all cows unsuccessfully attached by the teat cup attachment robot at second attempt were attached manually (i.e. with human assistance).

5.3.2 Historical data automatic milking system

To enable some level of benchmarking with current commercially available AMS equipment, historical electronic data were collected from VMSClient (DeLaval VMS™ support software). Data were selected from a period when the AMS was being managed as a '*commercial*' operation with limited research disruptions. Two discrete data periods were selected to create similar management conditions to the RR controlled trial. The first period of data collection (March 4–24, 2008, **AMS grass**) was during a period of no PMR (diet consisted of only grazed pasture and pelleted concentrates available in the AMS) (n = 131 lactating cows; average production 24.3 kg/day). As a result of the 'two way grazing system' (Kerrisk 2010) and the configuration of the cow traffic within and around the dairy, cows exiting one of the two available single-box AMS units had to pass through a smart selection gate (SSG) to get access to the day paddock, whilst cows exiting the other AMS had to pass through the SSG to traffic to the night paddock. Any incompletely milked cow that passed through the SSG after milking was drafted back into the dairy for a second milking attempt (maximum two consecutive times). The second data collection period (April 2–22, 2008, **AMS PMR**) was during a period of supplementation where cows gained access to PMR on a post-milking feed pad after each milking session prior to trafficking to pasture (n = 132 lactating cows; average production 22.7 kg/day). During this period some cows trafficked through a SSG after accessing the feed pad before being able to traffic to the pasture. It was at this post-feeding SSG passing that cows were drafted back to the pre-milking waiting area after an incomplete milking. To keep the selected data as similar as possible with the RR data, any cows with a milking interval (prior to first attempt) greater than 24 h where deleted (592 milk sessions, 6.7% of all milking sessions) from the dataset before the data were analysed.

5.3.3 Statistical analyses

5.3.3.1 Outcome variables

Two binary outcomes (yes/no) were measured in the RR study: (1) whether a cow incomplete at *first* attempt was subsequently complete at *second* attempt (RR-I); and (2) whether a cow was successfully milked *after two* attempts (RR-II). Electronic data collected by the management program were used to calculate the milking interval whilst the success of attachment at both the first and second attempts on the RR was recorded through visual observation.

Similar outcomes were measured in the historical data study: (1) whether a cow incomplete at *first* attempt was subsequently complete *at second* attempt (AMS-I); and (2) whether a cow was successfully milked *after an AMS visit* (combined first, second and third attempts) (AMS-II).

For both the RR- and AMS study univariable analyses were conducted to investigate the effect of individual quarters on the proportion of incomplete milked cows at the first attempt. The four quarters, left back, right back, left front and right front, as well as the 'back' (grouped; left back and right back) and 'front' quarters (grouped; left front and right front) were tested with their association of attachment failures.

5.3.3.2 Explanatory or predictor variables

For the AMS study, all historical data generated for the single-box AMS units were collected electronically and exported from the management program. These data included unsuccessful milkings recorded by the system, milking interval (time between milkings), production per day and milking station (cows had the choice of two AMS units).

Some additional electronic data for the RR study were collected to investigate the relationship between attachment success and stage of lactation (days in milk; DIM), parity (lactation number), production level (7-day average production), milking interval leading up to first attempt (hours since previous milking) and interval between first and second attempts.

It is note that the analysis of historical AMS data for the first outcome (AMS-I) was conducted with only cows in the AMS grass dataset with a milking interval (between 1st and 2nd attempt) shorter than two hours (n = 64), and cows in the AMS PMR dataset with a milking interval (between 1st and 2nd attempt) shorter than five hours (n = 50) were included. These selected milk data were isolated to create a comparable dataset with the RR milked cows which had a maximum of two (RR 1 h) and five hours (RR 3 h) between attempts.

5.3.3.3 Statistical models

The data were analysed with GenStat 13th Edition (VSN International, Hertfordshire, UK) with a similar approach used for all binary outcome variables. Initially, contingency tables of explanatory variables were created to make preliminary evaluations of the association of explanatory variables with the outcomes. Later, univariable generalised linear mixed models (GLMM) were built to test association of each explanatory variable (as described above for RR and AMS data) with outcome variables. Cow ID was included as a random effect in models for RR study (RR-I and RR-II) to take into account the multiple observations from each cow. Similarly, Cow ID and milking station (AMS1 or AMS2) were included as random effects in the models for historical data (AMS-I and AMS-II).

The assumption of linearity for quantitative variables was tested by categorizing variables by quartiles for all GLMM analyses. Categorised variables were used for further analyses, if this assumption was invalid. All variables with a P-value of < 0.25 in univariable analyses were included in the multivariable GLMM model. Insignificant variables ($P > 0.05$) were then eliminated using a backward stepwise approach. Odds ratios and their confidence limits from the final model were presented and discussed.

5.4. Results

The actual interval between first and second attempt averaged 1:03 (max. 2 h) and 3:30 (h:mm; max. 5 h) for the RR 1 h and RR 3 h treatments, respectively. The average milking interval of all the historical data after an incomplete milking was 8:15 and 9:00 (h:mm) for the AMS grass and AMS PMR datasets, respectively. Incomplete cows with a milking interval below two and five hours (AMS grass vs. AMS PMR respectively) resulted in an average milking interval of 0:50 (max 1:50 hrs; n = 64) and 2:46 h (max. 5:00 hrs; n = 50).

The descriptive statistics, presented in Table 5.1, show the attachment success of the first attempt, proportion of successful second attempts and the overall proportion of completely milked cows after two attempts.

Table 5.1: Number of incomplete milkings at a first milking attempt, successful milkings at second milking attempt and complete milkings after two attempts (with proportions between brackets)

Data	Treatment	Total	Incomplete at 1st attempt	Successfully attached at 2nd attempt	Completely milked after two attempts
Robotic rotary					
	RR 1 h	212	40 (0.190)	19 (0.48)	191 (0.90)
	RR 3 h	216	46 (0.210)	17 (0.37)	187 (0.87)
AMS					
	AMS grass	4009	253 (0.063)	185 (0.73)	3941 (0.98)
	AMS PMR	4200	192 (0.046)	149 (0.78)	4157 (0.99)

5.4.1 Difference in attachment success on individual quarters

Exploration of the RR results showed that the probability of incomplete milkings at first attempt was significantly different between individual quarters (Table 5.2). The probability of incomplete attachment was highest in left back teats as they were 3.3 times less likely to be attached compared with right front teats, which were most likely to be attached at first attempt. When comparing the combined front and back quarters, the front quarters were 2.5 times more likely to be attached successfully at first attempt.

Table 5.2: Univariable results to investigate the association of individual quarters on probability of incomplete at first attempt with the *robotic rotary*. Cow ID was included as a random effect in the model (back = left back + right back, front = left front + right front)

Variables	Categories	b	SE(b)	P-value	Odds ratio	95% CI^
Teat				<0.001		
	Left back	1.19	0.30		3.27	1.83, 5.84
	Right back	0.98	0.30		2.65	1.49, 4.74
	Left front	0.34	0.30		1.41	0.79, 2.52
	Right front	0				
Front and back quarters combined				<0.001		
	Front teats	0				
	Back teats	0.90	0.21		2.46	1.63, 3.71

^Confidence interval

Interestingly the historical AMS data indicated that the front teats were significantly less likely to be attached at first attempt as shown in Table 5.3.

Table 5.3: Univariable results to investigate the association of individual quarters on probability of incomplete at first attempt with the single-box AMS. Cow ID and device (AMS1/AMS2) were included as a random effects in the model (back = left back + right back, front = left front + right front)

Variables	Categories	b	SE(b)	P-value	Odds ratio	95% CI^
Teat				<0.001		
	Left back	0.52	0.13		1.68	1.32, 2.17
	Right back	0				
	Left front	0.43	0.13		1.53	1.18, 1.98
	Right front	0.78	0.13		2.18	1.68, 2.81
Front and back quarters combined				<0.001		
	Front teats	0.32	0.09		1.38	1.15, 1.65
	Back teats	0				

^Confidence interval

5.4.2 Results for robotic rotary dairy

5.4.2.1 Outcome RR-I: Successful attachment at second attempt

Probability of success at second attachment was not significantly different between 1 h and 3 h treatment but it was included in the multivariable model as it was the variable of primary interest. Of the other explanatory variables tested, only the average 7-day milk production was significant in the multivariable model (see Table 5.4).

Table 5.4: Final generalised linear mixed model to investigate the association of treatment and other variables with the first robotic rotary outcome variable–proportion of cows incomplete at first attempt which were subsequently complete *at second* attempt (RR-I). Cow ID was included as a random effect in the model

Variables	Categories	b	SE(b)	P-value	Odds ratio	95% CI^
Constant		-0.71	0.63			
Treatment				0.42		
	1 h	0				
	3 h	-0.41	0.51		0.66	0.24, 1.86
Milk yield 7 days				0.038		
	0–10.8	0				
	11.9–14.7	-0.004	0.80		0.99	0.19, 5.14
	14.8–19.2	0.51	0.78		1.66	0.34, 8.14
	≥19.3	2.01	0.79		7.47	1.48, 37.45

^Confidence interval

5.4.2.2 Outcome RR-II: Successfully milked after two attempts

Treatment and all other explanatory variables discussed above were also tested for their association with the second outcome–successful milking after two attempts. Only parity was significant in the final multivariable model whilst the treatment variable (the variable of main interest) was not significant (Table 5.5).

Table 5.5: Final generalised linear mixed model to investigate the association of treatment and other variables on the second robotic rotary outcome variable–proportion of all cows which were successfully milked *after two* attempts (RR-II). Cow ID was included as a random effect in the model

Variables	Categories	b	SE(b)	P-value	Odds ratio	95% CI^
Constant		1.47	0.41			
Treatment				0.144		
	1 h	0				
	3 h	-0.50	0.34		0.61	0.31, 1.19
Parity				0.003		
	1	0				
	2	0.96	0.43		2.61	1.13, 6.07
	3	1.84	0.43		6.32	2.72, 14.67
	≥4	1.82	0.43		6.16	2.65, 14.29

^Confidence interval

5.4.3 Results for automatic milking system

5.4.3.1 Outcome AMS-I: Successful attachment at the second attempt

After backwards elimination, the final GLMM results are presented in Table 5.6. There was a significant impact of milking interval and an increased daily milk production on attachment success rate after an incomplete milking but there was no significant difference between the different management systems (sending cows to a feedpad for an extended milking interval; non significant and deleted from final model).

Table 5.6: AMS) Final generalised linear mixed model to investigate the association of treatment and other variables with the first AMS outcome variable–proportion of cows incomplete at first attempt which were subsequently complete *at second* attempt (AMS-I, *selected milk data*). Cow ID and device (AMS1/AMS2) were included as random effects in the model

Variables	Categories	b	SE(b)	P-value	Odds ratio	95% CI^
Constant		0.46	0.75			
Milking interval[a]				0.037		
	<2 h (AMS grass)	0				
	<5 h (AMS PMR)	1.13	0.55		3.11	1.07, 9.05
Daily milk yield		0.08	0.03	0.003	1.09	1.03, 1.15

[a] Selected cows with a milking interval prior to 2nd attempt < 2 hours (AMS grass; n = 64) and < 5 hours (AMS PMR; n = 50)
^Confidence interval

5.4.3.2 Outcome AMS-II: Successfully milked after an AMS visit

The effects of the explanatory variables on the success of attachment of all the recorded milkings are presented in Table 5.7 (the proportions of all cows which were successfully milked after an AMS visit-including 1st, 2nd and 3rd attempts). Non significant explanatory variables were excluded by backward elimination.

Table 5.7: AMS) Final generalised linear mixed model to investigate the association of explanatory variables with the second outcome variable–the proportions of all cows which were successfully milked after an AMS visit (AMS-II). Cow ID and device (AMS1/AMS2) were included as random effects in the model

Variables	Categories	b	SE(b)	P-value	Odds ratio	95% CI^
Constant		2.93	0.71			
Treatment				<0.001		
	AMS grass	0				
	AMS PMR	0.48	0.11		1.61	1.95, 2.01
Milking interval		0.10	0.01	<0.001	1.10	1.08, 1.13
Daily milk yield		0.08	0.01	<0.001	1.09	1.07, 1.10

^Confidence interval

5.5. Discussion

It is recognise that cup attachment is highly influenced by sensor cleaning status, camera version, robot arm maintenance and other parameters. Minimizing incomplete attachments in any automated milking system can be achieved through good cow/udder management (e.g. maintaining healthy teats and quarters, minimizing excessively hairy udders, minimizing the level of soiling on the udder) and good machine management (regular maintenance, servicing and machine performance monitoring). The AMS data shown here are not intended to be used as a comparison between the two technologies (the AMS and RR), however with a lack of published data on reattachment success with AMS in a pasture-based system, historical data is shown in this study to create a benchmark level for this specific management situation.

There was no significant difference found between the frequency of successful attachment at second attempt in neither the **RR 1 h** and **RR 3 h** treatments, nor the **AMS grass** and **AMS PMR** datasets. It is likely that the additional 2.5 h waiting period (for the **RR 3 h** treatment) was insufficient to cause any dramatic changes in udder conformation that might have otherwise resulted in a treatment effect. The impact of length of post-milking period on cisternal milk volume would be largely dependent on the production level of the cow (Knight et al. 1994). Knight et al. (1994) reported that cisternal milk volume remained low (600 g or less) until four hours after milking with two groups of cows producing 28 and 15 litres. A similar study by Stelwagen (1996) reported that whilst the volume remained low until seven or eight hours post milking, the cisternal compartments actually started filling immediately after milking.

The results presented here are particular to pasture-based cows which will have a lower energy intake than cows in an indoor system fed a high energy total mixed ration (TMR; Bargo et al. 2002, 2003). In addition to milking frequency, energy intake has a major effect on production level, as shown in a study by Utsumi (2011). It was shown that when cows were managed on pasture, with the availability of 1 kg concentrate per 4 kg milk in the AMS stall, the limiting factor in milk production was energy intake levels rather than milking frequency. When energy intake is not the limiting factor (during periods of a complete TMR diet) the greatest factor affecting production level was the milking frequency (Utsumi 2011). Under such circumstances the effect of an extended interval between two attempts could be greater as the udder fills more rapidly.

A small number of studies around current AMS technology have noted the relationship between udder shape and attachment success rate at first attempt (Svennersten-Sjaunja and Pettersson 2008; Rossing and Hogewerf 1997). Differences in attachment success between front and back quarters have also been recognised (albeit not quantified) in studies with a single unit AMS (Capelletti et al. 2004; Hamann et al. 2004). These studies showed that back quarters were more difficult to attach for an automatic cup attachment robot.

In the data presented here it was evident within the analyses of the RR data that back quarters were at a higher risk of not being attached at first attempt (compared to front teats) which may have been due to udder conformation and a closeness of back teats that made automatic cup attachment more challenging. However the AMS data showed a much smaller difference in the initial success between front and back teats with front teats being more likely to be unsuccessfully attached at first attempt.

The difference in attachment performance (between AMS and RR) could be caused by one (or a combination) of the many differences between the two technologies. It is not possible in this chapter to describe all of the differences but some of the potential contenders (among others) could be; the difference in angle of the robot to the cow, the fact that the RR platform rotates and the cow stands differently to brace herself, a potential cow behavioural change resulting from the presence of adjacent herd mates rather than being solitary, particular differences in the attachment and position tracking hardware and software.

One of the key differences in technology functionality (between AMS and RR) is that the AMS has the opportunity to have several attachment attempts whilst the cow is in the crate for an entire milking session. Conversely, the RR has only one opportunity to attach milking cups per rotation. Each milking cup was collected by the robotic arm only once while the cow was in the attachment bail, after the attachment the cow was rotated to the next position on the rotary. It could be considered worthwhile to have the robotic cup attachment arm collect cups again and take additional attempts to attach individual cups prior to allowing the cow to rotate to the next bail. However, the impact on throughput and milk harvesting rates would obviously be negatively affected and this needs to be weighed up against the loss in efficiency caused by milking 20% of cows a second time.

In the RR study it was found that cows with a production level higher than 19.3 kg/d were up to 7 times more likely to result in a successful and complete milking at second attempt compared to cows producing less than 11 kg (RR-I). When looking at the selected AMS milk data (< 2 and < 5 h milking interval after incomplete attachment) it was also shown that cows with higher production levels were associated with a higher likelihood of attachment at second attempt (AMS-I). The higher production level would likely be associated with a fuller and more distended udder which may have made it easier for any automatic cup attachment device to locate the teats.

The AMS data showed that higher daily production levels and longer milking interval were both likely to result in a higher chance of a successful attachment after any visit to the AMS (AMS-II).

The significant impact of only parity on the second outcome variable–proportion of all cows which were successfully milked after two attempts (RR-II), generated from the RR data, was somewhat surprising. The impact of parity would likely be largely created by changes in udder conformation and the more difficult shaped (compact and higher) udders often associated with younger cows. Some of the parity effect may also be attributed to animal behaviour. Not surprisingly different udder shapes have been reported to result in variable attachment success in AMS in other studies (Migliorati et al. 2004). This effect requires further investigation as the most suitable management of incompletely milked younger cows could be different to that of older cows.

Longer milking intervals were expected to be associated with a higher level of udder fill (as reported by Knight et al. 1994 and Stelwagen et al. 1996) and therefore a higher likelihood of successful attachment. However, this was probably confounded with expected yield at each milking session as longer intervals were more likely associated with later stages of lactation (Svennersten-Sjaunja and Pettersson 2008). Days in milk was not a significant variable in the model reported in the presented study, despite the expectation that attachment difficulty could increase with higher days in milk due to the udder being more flaccid. A study performed by Bader et al. (2001)reported the change in udder conformation during the lactation of a cow, and noted that this could affect the success of attachment rate in an AMS.

It is also important to mention that ongoing development of the technology prior to full commercialisation of the product will undoubtedly result in improved performance of the technology and will likely impact on the absolute incidence of incompletes at first attempt. However, it is anticipated that the trends and treatment differences indentified in the presented work will likely remain unchanged. It is also anticipated that the learnings from the work presented here will continue to have relevance when the layout and cow trafficking routes of new AMS and RR installations are being considered, particularly where these include a post-milking feeding area. Whilst the impact on milk yield of effectively extending the interval between milking for the individual quarter(s) that were not successfully attached at first attempt was not measured in this study, it would be likely that a prompter return for the second attempt would be beneficial to short term milk production and udder health.

5.6. Conclusions

The results presented here, generated with a prototype RR, have application for dairy design and cow traffic management with both AMS and RR installations. Because this research was conducted on one of just three installations of the prototype RR globally, literature pertaining to this type of system does not exist, indicating that the findings presented here are invaluable to furthering industry understanding of management with this new milk harvesting technology. The system showed no "attachment success" differences between milking incomplete cows after one hour (**RR 1 h**) or three hour (**RR 3 h**) intervals in the study presented here. This suggests that there is a level of flexibility available in designing the dairy layout and that no significant advantage or disadvantage (with regard to subsequent success level) exists in drafting cows directly back to the pre-milking yard after an incomplete milking or after visiting a feedpad. The observed 10% incomplete milked cows, after two milking attempts, is of concern in regards to potential cow health issues and has raised awareness to consider additional preventive measures increasing the success rates of the RR.

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Chapter 6. General discussion and conclusions

General discussion and conclusions

The work presented in this thesis encapsulates original research and essential new knowledge and information regarding the feasibility and operational efficiency of incorporating a novel prototype robotic rotary (RR) into a low-input, pasture-based Australian dairy farming system. The general aim of the research was to evaluate the potential throughput, performance and limitations of a world's first high throughput automatic milking system (AMS), with a key interest in creating a level of understanding within the industry of management options with this new milk harvesting technology.

It is known that the Australian dairy industry is predominately pasture-based, and relies on the ability to have cows grazing throughout the year. Grazing systems are generally acknowledged to be the most cost efficient in producing milk (Dillon 2005). As a result the research and knowledge developed around the typical AMS housed dairy farming systems, most commonly implemented in Europe, are not entirely applicable to Australian dairy farms. The Greenfield project (Hamilton, New Zealand) and the FutureDairy project (Camden, NSW, Australia) have investigated the feasibility of incorporation of AMS into pasture-based dairy farming systems and concluded that cows in a pasture-based system adapt very well to voluntary AMS with the use of food incentives (Jago et al. 2002; Davis et al. 2008b).

Whilst high adoption rates of AMS have been observed around the world, the rate of adoption on larger scaled farms has been significantly lower compared to smaller scaled, family farms. The higher capital investment cost of AMS (particularly in relation to investment cost/cow) on larger farms compared to a conventional milking system (CMS) is frequently claimed as being one of the main causes of the lower adoption rate. The study by Armstrong et al. (1997) suggested that the investment cost of AMS should be reduced before AMS becomes a financially viable option for farms milking more than 500 cows. Results of a recent survey, conducted in 20 European countries with 2,600 farms, showed that the proportion of large farms (> 500 cows) using AMS was negligible (Lassen et al. 2012). This trend, which is also recognised by manufactures of AMS technology and as a result of the larger herd sizes commonly managed in Australia (compared to European herds), has been a key driver for the development of the RR (R. Mulder, DeLaval, pers. comm.). The RR was designed as a high throughput AMS that was intended to have a 'comparable' capital cost to CMS for medium to large herds, to deal with economies of scale and reduce the cost per kg milk harvested on the farm. The RR, as a high throughput AMS, has the potential to become the next solution for the automation of milk harvesting with larger scaled dairy herds (Rosengren 2010b).

However, whilst the RR is a type of AMS, it was not designed with all of the functionality of the commercially available single- and multi-box AMS units. Throughout its development much discussion and decision making has occurred to decide on functions that are necessary to allow the RR to operate with remote supervision and limited regular attendance from farm staff. There is recognition that the functions of fully automated system rinsing and washing and individual cow in-bail feeding are functions that are available on existing AMS units. However, inclusion of these functions in the RR would be technically possible but would also erode the economic advantage of the RR with its current level of functionality. Economic and sustainable solutions will be driven by consumer and producer demands with the expectation and anticipation that equipment manufacturers will step up and respond with economically viable solutions (R. Mulder, DeLaval, pers. comm.).

Being the first farm internationally to tackle voluntary distributed cow traffic (instead of batch milking) the challenges presented in this thesis were specific to the system utilisation and the stage of technological development of the Camden prototype installation. The author acknowledges that with further developments of the RR in the future, some of the operational challenges presented here may be solved. It is also possible that different versions of the RR may be available in the future to allow for different levels of investment and in particular with specific functionalities that might be tailored to suit different farm management and system solutions (e.g. batch vs. voluntary cow traffic; R. Mulder, DeLaval, pers. comm.).

Thus, investigations into the feasibility and operational efficiency of the novel prototype RR into a low-input, pasture-based Australian farming system were imperative to ensure system management knowledge was generated. Firstly in Chapter 2, the performance and challenges faced with the RR operational in a pasture-based system, installed, tested and co-developed since 2009 at the Elizabeth Macarthur Agricultural Institute (Camden, NSW, Australia), were indentified. Three main focus areas were determined in this Chapter, which constituted the basis of the research program presented in this thesis. Firstly, a typical voluntary movement of the cows around the system was found to be comparable with the findings previously presented by Kerrisk (2010) around single-box AMS in a pasture-based system. Secondly, the attachment success as well as the attachment speed were found to be significantly affected by several factors. The third point of interest found was the effect of milking interval after an incomplete milking on attachment success at a second milking attempt.

As indicated, in the first commercially released version of the RR a fully automated wash function is not integrated within the design. In Chapter 3 a coping mechanism was tested to ensure the collection and storage of high quality milk could be maintained during periods of underutilisation of the systems' capacity in a voluntary setting. The results of this study showed that bails can be disabled without any negative impacts on cow traffic onto the RR platform.

Feed availability had a positive effect to entice cows to enter RR platform, however, there was no effect found of the different bail activation sequences on cow traffic. It is acknowledged that, as the RR does not have the ability to conduct targeted individual cow feeding, a stronger statistical model with a cross-over design could not be implemented. Aside from the lack of ability to feed some cows and not others, the cows used for the study were all accustomed to receiving feed upon entry to the RR. The effect of the availability of feeding on the RR in a herd of cows that are not used to receiving feed is unknown. It is also unknown what the effect would be of not supplying feed while introducing and training a group of cows, previously milked in a CMS with in-bail feeding, to a new RR dairy installation on their voluntary cow traffic movement. Further studies with inexperienced cows would need to be conducted to increase our knowledge of the effect of use of feed on RR cow traffic. The installation of the RR at Camden was a prolonged process of intermittent testing and many cows gained experience with the equipment in a batch milking setting prior to voluntary cow traffic being implemented. Incorporation of the feed incentive was tailored to assist the cows with the process of adapting to voluntary cow traffic in a setting where they had previously been batch milked. Whilst the availability of feed in an AMS is known to impact on the voluntary visits to the system as presented in several previous studies (Halachmi et al. 2005; Bach et al. 2007) there are no reported studies on operation of AMS with no in-bail feeding from the day of commissioning.

As all cows in a large herd will enter the RR through a single entry point, future studies into cow behaviour and queuing in relation to feed availability and other factors need to be conducted to better understand factors impacting cow traffic. In addition it was shown in this study (Chapter 3) that more consecutive instead of alternated activate bails will result in a higher harvesting efficiency of the system. Poor cow traffic, leading to bails remaining idle, will also result in less robot actions being conducted simultaneously resulting in a lower harvesting efficiency.

Higher harvesting efficiencies are expected in the RR compared to traditional AMS. It is known that the robotic arm of single-box AMS stays with the cow during the entire milking. On the other hand, the robotic arm of the RR remains stationary while the platform rotates cows away from the robotic arm after cup attachment, thereby, leading to a higher efficiency of the robotic devices. The negative impact of this design is that any missed attachments by the automatic cup attacher (ACA) are not attended again and the cow leaves the system incompletely milked, lowering the harvesting efficiency. Mainly due to this design, as a high throughput prototype AMS, the observed attachment accuracy was lower than desirable. Furthermore the effect of premilking teat preparation on oxytocin (OT) levels is also known to impact the harvesting efficiency (Bruckmaier et al. 2001). Chapter 4 reports on the investigations conducted to assess the effects of not using premilking teat preparation on attachment accuracy and milk removal characteristics. It was shown that teat cups were attached more successfully and faster when cows were subjected to premilking teat preparation treatment. It is acknowledged that the impact on the health of the cow related to premilking teat preparation was not investigated in this study as the main aim was to determine the impact of the preparation on attachment accuracy. Longer term studies would be necessary to further investigate the impact of not using a teat preparation module (TPM) on the udder health of cows and on bulk milk quality. This is because premilking teat cleaning is known to remove significant amounts of bacterial spores from the teats, resulting in cleaner milk collected during milking (Melin et al. 2004).

Finally, whilst there was an impact on attachment success by the use of a premilking treatment, the overall level of success was still lower than desirable based on previous similar studies in AMS (Bach and Busto 2005; Gygax et al. 2007). This acted as the precursor for a study into different management practices of previous incompletely milked cows (presented in Chapter 5). No difference was found in attachment success when milking these cows after a one or a three hour interval between first and second attempts, in two different management situations (drafting cows directly back to the pre-milking yard or after visiting a feedpad). It is recognised that it would have been better to conduct this study over a longer period of time, yet it is difficult to control the milking interval of cows volunteering around the RR. In addition during the period of the trial the RR was intermittently operational, which means that between the observed milking the cows were voluntarily milked in the AMS units. Therefore the decision was made to conduct a relatively short study with a controlled cow traffic system. This resulted in defined milking intervals. The historical AMS study, with selected data, corresponded with the RR data and showed that no difference in attachment success is to be expected while milking cows for a second time (after an incomplete milking event) at one- or three-hour milking intervals. In addition it is acknowledged that different management strategies might suit different groups of cows. This was however not investigated in this study and could be an area for future investigation with the RR. Also worth mentioning is that an unpublished investigation was conducted with the RR whereby operators manually instructed the ACA to reattempt attachment when an incomplete attachment occurred. This study (Kolbach, unpublished data) showed that up to 50% of the missed teats could be attached successfully while the cow was still in the attachment bail without any negative impact on other teats being milked. However, whilst the attachment time of the specific milking was increased, not having cows re-entering the system and occupying a bail for a full reattachment attempt resulted in an overall lower robotic time per cow. The author acknowledges that as the system capabilities improve, the requirement for assessing different management strategies (for incompletely milked cows) is reduced but will never be eliminated completely.

The author acknowledges that a large variety of farm systems exist throughout Australia, generally split into five main feeding systems (Little 2010; Dairy Australia 2010b), and an even bigger spectrum of feeding system are evident at an international level. Therefore, the results of these investigations will need to be taken with caution when applied to future RR operations implemented in contrasting feeding systems. Although this work has contributed to the development of the RR system, the results presented are relatively specific to the situation and environment in which the RR was installed and operated. Furthermore as the results in this thesis were generated with a prototype RR, the technological improvements are expected to result in improved attachment success of the commercial versions of the system. Hardware and software updates conducted since the reported studies have already resulted in improvements of the attachment success, even with the prototype RR. As the RR is already commercially released and will continue to undergo changes and be installed in different farming systems, new research opportunities will arise. This is particularly important when considering the potential RR throughput in different scenarios, where cows can be milked in a voluntary or batch milking system. Opportunities and a demand for the development of dynamic models will also arise, to predict the operational efficiency of the RR in many different farm scenarios across the world, as carried out in previous studies around traditional AMS technology (Cooper and Parsons 1998; Halachmi et al. 2001; Rotz et al. 2003). These models will have the potential to support large-herd operations in the decision making process regarding installation and operation of high throughput AMS.

The results of this study indicate that, regardless of which operational challenges may be faced, the use of accurate management practices with the RR will result in increased operational efficiency. To overcome periods of underutilisation of the systems' capacity, bails can be disabled without having a negative effect on cow traffic'; nevertheless it is advisable to activate consecutive bails to allow an increased harvesting efficiency to be realised. However as a feeding system is not available on the first released commercial RR versions, it is advisable to have some sort of feed availability upon entry of the RR, as a significant negative effect on cow traffic was found when no feed was available on the RR platform. Reduced cow traffic as a result of the absence of feed will result in a decreased operational efficiency. It is also advisable to install the RR equipped with a TPM, as premilking teat preparation was positively associated with an increase in attachment accuracy and a decreased attachment time, resulting in an increased milk harvesting efficiency. Even though attachment accuracy was improved after premilking teat preparation, there were a number of cows leaving the RR incompletely milked, as with any AMS. The milking interval between the incomplete milking and the second attempt at milking did not affect the attachment success rate at the second attempt. This means that farmers have a level of flexibility when designing dairy layouts.

In addition to the practical applications presented above and despite the challenges presented in this thesis being specific to the system utilisation and the stage of technological development of the Camden installation, it is concluded that the research reported in this thesis has contributed new knowledge around the throughput, performance and potential limitations of the RR. The importance of research and development is highlighted in a publication of Freeman and Soete (1997), showing that researching new technologies plays a major role in improving the final version through an increased scientific knowledge and with scientific publications as a result. Research and development and testing of prototypes, as conducted in this thesis, are recognised to be critical with successful introduction of innovative technologies (Rothwell 1992). Similar studies around prototype AMS were conducted in the 1980s, and reported on the physical problems concerning the automatic attachment of teat-cups (Ordolff 1984), resulting in improved AMS performance before becoming commercial available. As the RR is due for commercialisation in 2012 and there is no published literature pertaining to any aspect of the RR, the findings presented here are invaluable to furthering industry understanding and knowledge. This knowledge will help researchers, farm managers and developers of the system in their bid for successful adoption of the RR on commercial farms and for further development and enhancement of the performance of the RR.

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