Automating the milking process within a grass-based system

John Shortall
Department of Biological Sciences, Cork Institute of Technology, Cork, Ireland

Follow this and additional works at: https://sword.cit.ie/allthe

Part of the Agriculture Commons, and the Dairy Science Commons

Recommended Citation
Shortall, John, "Automating the milking process within a grass-based system" (2017). Theses [online]. Available at: https://sword.cit.ie/allthe/51

This Doctoral Thesis is brought to you for free and open access by the Dissertations and Theses at SWORD - South West Open Research Deposit. It has been accepted for inclusion in Theses by an authorized administrator of SWORD - South West Open Research Deposit. For more information, please contact sword@cit.ie.
Automating the milking process within a grass-based system

John Shortall

Ph.D. 2017
Automating the milking process within a grass-based system

A Thesis Submitted to
Cork Institute of Technology for the Degree of
Doctor of Philosophy

By
John Shortall (B.Agr.Sc.)

1Department of Biological Sciences, Cork Institute of Technology,
Bishopstown, Co. Cork, Ireland

2Teagasc, Animal & Grassland Research and Innovation Centre,
Moorepark, Fermoy, Co. Cork, Ireland

Research Supervisors

1 Dr. Roy Sleator
2 Dr. Bernadette O’Brien

Submitted to Cork Institute of Technology, September 2017
Declaration

I hereby certify that the work embodied within this thesis is entirely my own work, except where otherwise accredited; and that this thesis has not previously been submitted for an award at any other institution.

Signed: John Shortall (Candidate)  Date: 29/09/2017

Signed: Roy Sleator (Supervisor)  Date: 29/09/2017

Signed: Bernadette O'Brien (Supervisor)  Date: 01/09/2017
Table of Contents

List of Tables.........................................................................................................................vi
List of Figures .......................................................................................................................ix
Glossary of Terms .................................................................................................................xii
Acknowledgements ............................................................................................................ xiv
Abstract .............................................................................................................................. xv
Chapter 1: General Introduction...........................................................................................1
Chapter 2: Literature review .................................................................................................8
  2.1 Introduction...................................................................................................................9
  2.2 The dairy industry in Ireland .....................................................................................9
    2.2.1 General industry description ............................................................................9
    2.2.2 Production system overview ..........................................................................11
    2.2.3 Challenges facing Irish dairy farms .................................................................14
  2.3 Automatic milking.................................................................................................17
    2.3.1 Background to automatic milking .....................................................................17
    2.3.2 Automatic milking in combination with grazing .............................................18
  2.4 Factors associated with AM sustainability .............................................................20
    2.4.1 Social sustainability ........................................................................................20
    2.4.2 Environmental Sustainability ..........................................................................25
    2.4.3 Economic Sustainability ..................................................................................30
  2.5 Factors affecting voluntary cow traffic in an AM systems ......................................34
    2.5.1 Pasture allocation ..........................................................................................35
    2.5.2 Pasture cover ..................................................................................................38
    2.5.3 Distance to pasture .......................................................................................39
    2.5.4 Climate ..........................................................................................................40
    2.5.5 Water availability .........................................................................................41
    2.5.6 Supplementation ...........................................................................................42
    2.5.7 Stage of lactation .........................................................................................43
    2.5.8 Parity .............................................................................................................44
    2.5.9 Breed .............................................................................................................45
    2.5.10 Social Hierarchy ..........................................................................................46
  2.6 Conclusions and research possibilities .....................................................................48
Chapter 9: Publications .................................................................225
  9.1 Peer Reviewed Journal Publications ......................................226
  9.2 Conference Publications .....................................................226
  9.3 Technical Articles .................................................................228
Chapter 9: Appendix ...................................................................229
List of Tables

Table 2.1 Summary of the change in labour associated with the use of automatic milking (AM) systems as identified by seven studies in six countries .............................................. 23

Table 3.1 Characteristics and infrastructure of the seven automatic milking (AM) study farms ..................................................................................................................................... 60

Table 3.2 Breakdown of the consumption and cost of electricity per litre of milk sold and per cow on the seven study farms for a 12 month period .............................................. 62

Table 3.3 The average electricity consumption and cost per individual automatic milking unit for the average AM unit, a single unit configuration and double unit configuration. Data is presented on an annual, per milking day and per milking event (ranges in parenthesis) ............................................................................................................. 64

Table 3.4 Total direct water use on the seven study farms for a 12 month period ............. 70

Table 3.5 The average water consumption per individual automatic milking unit for the average AM unit, a single unit configuration and a double unit configuration. Data is presented on an annual, per milking day and per milking event (ranges in parenthesis) ................................................................. 71

Table 3.6 The proportion of tube-cooler recycled to water consuming process and the proportion of total water for each of those processes obtained from the tube-cooler .... 71

Table 4.1 Financial and biological assumptions used in the Moorepark Dairy Systems Model .................................................................................................................................... 93
Table 4.2 Initial machine and infrastructural investment costs and annual machine maintenance and running costs for three types of milking technology on two farm sizes, MF (medium farm) and LF (large farm) ................................................................. 97

Table 4.3 Average dairy labour input (h/cow per year) for combined and specific dairy tasks on farms milking with automatic milking (AM) and conventional milking (CM) systems ................................................................................................................................ 102

Table 4.4 Effect of milking system type on annualized dairy farm output variables (10-year period after installation) for three types of milking technology on two farm sizes, MF (medium farm) and LF (large farm) ............................................................................ 103

Table 4.5 Annual (for 10-years after the investment) and total discounted net profit (€ with discounted net cash flow included in parentheses) for three types of milking technology on two farm sizes, MF (medium farm) and LF (large farm) ........................................ 106

Table 4.6 Return on additional investment (%) above the base after the 10-year period for three types of milking technology on two farm sizes, MF (medium farm) and LF (large farm) .......................................................................................................................... 107

Table 4.7 The effect of milk price, capital costs, labour costs and interest rates sensitivity analysis on total discounted net profit for three types of milking technology on two farm sizes, MF (medium farm) and LF (large farm) ................................................. 110

Table 5.1 Grazing and grass quality characteristics during the early and late lactation experimental periods .................................................................................................................................. 136

Table 5.2 Quality of the concentrate consumed during early and late lactation experimental periods ........................................................................................................................................... 136
Table 5.3 The effect of low concentrate (LC) and high concentrate (HC) supplementation levels on daily milking frequency, milking interval and milking event outcome as a proportion of total milking events in early and late lactation .......... 139

Table 5.4 The effect of low concentrate (LC) and high concentrate (HC) supplementation levels on milk production and milking characteristics in early and late lactation ............................................................................................................................... 140

Table 5.5 The effect of low concentrate (LC) and high concentrate (HC) supplementation levels on cow traffic and activity in early and late lactation .......... 142

Table 6.1 Grazing characteristics and grass quality combined for each of the three grazing sections .................................................................................................................. 163

Table 6.2 The effect of breed on milking frequency, milking interval, milk yield and milking event outcome .................................................................................................................................................. 167

Table 6.3 Effect of breed on return time, wait time and activity in a pasture-based automatic milking system ............................................................................................................................................. 168

Table 6.4 Effect of breed on milking characteristics in a pasture-based automatic milking system .............................................................................................................................................. 170
List of Figures

Figure 2.1  Glanbia milk price 1999 to 2014 (LTO-International Milk Price Comparison)........................................................................................................................10

Figure 2.2  The seasonal grazing system; cows are calved and dried off to ensure synchrony between herd demand and feed supply............................................................12

Figure 2.3  Breakdown tasks on with a CM farm as a proportion of total labour input associated with the dairy enterprise (O'Donovan et al., 2008)........................................15

Figure 3.1  The relationship between (a) the number of milkings/AM unit per day and daily electricity consumption per AM unit and (b) the number of milkings/air compressor per day and daily electricity consumption per air compressor. Daily electricity consumption is expressed as kilowatt-hours and watt-hours per litre of milk produced. Each data point represents the average number of milkings/day and the average consumption/day for each of the 12 months in the study period for six of the study farms...........................................................................................................................65

Figure 3.2  Seasonal trend in total electricity consumption for the average of seven pasture-based automatic milking study farms over a 12 month period, expressed in kilowatt-hours (kWh) and watt-hours/litre of milk produced (Wh/L)..............................................67

Figure 3.3  Average percentage of daily total electricity consumption on-farm in (a) early lactation (March 24 to 25, 2015) (b) peak lactation (May 25 to 26, 2015) and (c) late lactation (September 15 to 16, 2015) for seven pasture-based commercial automatic milking farms.......................................................................................................................68
Figure 3.4 Seasonal trend in total farm direct water consumption for the average of seven automatic milking study farms over a 12 month period, expressed in litres and litres of water/litre of milk produced (L/L). Seasonal livestock/miscellaneous water consumption is also outlined in litres.

Figure 3.5 Average percentage of daily total direct water consumption on-farm in (a) early lactation (March 24 to 25, 2015) (b) peak lactation (May 25 to 26, 2015) and (c) late lactation (September 15 to 16, 2015) for seven pasture-based commercial automatic milking farms.

Figure 5.1(a) The combined total number of pre-selection gate passes for both treatments in the early lactation period, represented as an hourly proportion of the total. The time below each bar represents the hour that the gate passes occurred (i.e. bar 10 represents the gate passes that occurred between 1000 h - 1100 h).

Figure 5.1(b) The effect of low concentrate (LC) and high concentrate (HC) supplementation levels in early lactation on the average hourly distribution of gate passes (gate passes/treatment as a percentage of total gate passes at each time point). The time below each bar represents the hour that the gate passes occurred (i.e. bar 10 represents the gate passes that occurred between 1000 h - 1100 h). Hours with significantly different throughput between treatments ($P < 0.05$) are identified accordingly (*). The vertical bar represents the average standard error of the difference.

Figure 5.2(a) The combined total number of pre-selection gate passes for both treatments in the late lactation period, represented as an hourly proportion of the total. The time below each bar represents the hour that the gate passes occurred (i.e. bar 10 represents the gate passes that occurred between 1000 h - 1100 h).
Figure 5.2(b) The effect of low concentrate (LC) and high concentrate (HC) supplementation levels in late lactation on the average hourly distribution of gate passes (gate passes/treatment as a percentage of total gate passes at each time point). The time below each bar represents the hour that the gate passes occurred (i.e. bar 10 represents the gate passes that occurred between 10:00 - 11:00 h). Hours with significantly different throughput between treatments ($P < 0.05$) are identified accordingly (*). The vertical bar represents the average standard error of the difference ................................. 145

Figure 6.1(a) The combined total number of milkings for all cow breeds, represented as an hourly proportion of the total. The time below each bar represents the hour that the milking occurred (i.e. bar 10 represents the milkings that occurred between 1000 h - 1100 h) .............................................................................................................................. 169

Figure 6.1(b) The effect of cow breed (HF: Holstein Friesian; JEX: Jersey x Holstein Friesian; NRX: Norwegian Red x Holstein Friesian) on the average hourly distribution of milkings (milkings/breed as a percentage of total milkings at each time point). The time below each bar represents the hour that the milkings occurred (i.e. bar 10 represents the milkings that occurred between 1000 h - 1100 h). Hours with significantly different throughput between breeds ($P < 0.05$) are identified accordingly (*). The vertical bar represents the average standard error of the difference ............... 169
## Glossary of Terms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>12HS</td>
<td>12 Unit High Specification</td>
</tr>
<tr>
<td>12MS</td>
<td>12 Unit Medium Specification</td>
</tr>
<tr>
<td>20HS</td>
<td>20 Unit High Specification</td>
</tr>
<tr>
<td>20MS</td>
<td>20 Unit Medium Specification</td>
</tr>
<tr>
<td>ADF</td>
<td>Acid Detergent Fibre</td>
</tr>
<tr>
<td>AM</td>
<td>Automatic Milking</td>
</tr>
<tr>
<td>AMS</td>
<td>Automatic Milking System</td>
</tr>
<tr>
<td>AMS-DU</td>
<td>Automatic Milking System Double Unit</td>
</tr>
<tr>
<td>AMS-SU</td>
<td>Automatic Milking System Single Unit</td>
</tr>
<tr>
<td>CF</td>
<td>Crude Fibre</td>
</tr>
<tr>
<td>CM</td>
<td>Conventional Milking</td>
</tr>
<tr>
<td>CP</td>
<td>Crude Protein</td>
</tr>
<tr>
<td>DHA</td>
<td>Daily Herbage Allowance</td>
</tr>
<tr>
<td>DIM</td>
<td>Days in Milk</td>
</tr>
<tr>
<td>DM</td>
<td>Dry Matter</td>
</tr>
<tr>
<td>DMI</td>
<td>Dry Matter Intake</td>
</tr>
<tr>
<td>€</td>
<td>Euro</td>
</tr>
<tr>
<td>EBI</td>
<td>Economic Breeding Index</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>FTE</td>
<td>Full Time Equivalent</td>
</tr>
<tr>
<td>h</td>
<td>Hour</td>
</tr>
<tr>
<td>ha</td>
<td>Hectare</td>
</tr>
<tr>
<td>HC</td>
<td>High Concentrate</td>
</tr>
<tr>
<td>HF</td>
<td>Holstein Friesian</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>HS</td>
<td>High Specification</td>
</tr>
<tr>
<td>JEX</td>
<td>Jersey x Holstein Friesian</td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>km</td>
<td>kilometre</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt-hour</td>
</tr>
<tr>
<td>L</td>
<td>Litre</td>
</tr>
<tr>
<td>LC</td>
<td>Low Concentrate</td>
</tr>
<tr>
<td>LF</td>
<td>Large Farm</td>
</tr>
<tr>
<td>MDSM</td>
<td>Moorepark Dairy Systems Model</td>
</tr>
<tr>
<td>MF</td>
<td>Medium Farm</td>
</tr>
<tr>
<td>min</td>
<td>Minute</td>
</tr>
<tr>
<td>MS</td>
<td>Medium Specification</td>
</tr>
<tr>
<td>NDF</td>
<td>Neutral Detergent Fibre</td>
</tr>
<tr>
<td>NIR</td>
<td>Near Infrared Reflectance</td>
</tr>
<tr>
<td>NRX</td>
<td>Norwegian Red x Holstein Friesian</td>
</tr>
<tr>
<td>OMD</td>
<td>Organic Matter Digestibility</td>
</tr>
<tr>
<td>R^2</td>
<td>R squared (coefficient of determination)</td>
</tr>
<tr>
<td>ROI</td>
<td>Return on Investment</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>SE</td>
<td>Standard Error</td>
</tr>
<tr>
<td>sec</td>
<td>Second</td>
</tr>
<tr>
<td>SEM</td>
<td>Standard Error Mean</td>
</tr>
<tr>
<td>TDNCF</td>
<td>Total Discounted Net Cash Flow</td>
</tr>
<tr>
<td>TDNP</td>
<td>Total Discounted Net Profit</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>WAN</td>
<td>Wide Area Network</td>
</tr>
<tr>
<td>Wh</td>
<td>Watt-hour</td>
</tr>
<tr>
<td>YCO</td>
<td>Yield Carry Over</td>
</tr>
</tbody>
</table>
Acknowledgements

I would like to acknowledge the opportunity presented to me by Teagasc to carry out this research at the Animal & Grassland Research and Innovation Centre, Moorepark. I am grateful to Dr. Pat Dillon, Head of Centre, for making the necessary facilities available to me and the Teagasc Walsh Fellowship Scheme and the EU Autograssmilk project for the funding.

I would like to express my gratitude to Dr. Bernadette O'Brien for affording me the opportunity to be part of this research project and for the support and guidance shown throughout my time at Moorepark. I also thank Dr. Cathriona Foley for her help and advice and for the time and effort you put into this research. Thank you also to Dr. Roy Sleator of Cork Institute of Technology for the assistance provided and for the speedy response to any query I may have had. I am also grateful to Dr. John Upton and Dr. Laurence Shalloo for your contributions to my work.

The contribution of the technical staff - James Daunt, Kevin Hegarty, Kevin McNamara, Pat O'Connor, Mick Feeney (RIP), Andy McGrath and Christina Fleming - is greatly appreciated. I would also like to thank Joe Kirk (Acorn Ag. Research) and the many work placement students who contributed to the data collection for this work.

To the many friends I have made during my time in Moorepark, in particular my office mates Diarmuid, Alan, Nuria, Justine and Jessi for the priceless entertainment provided over the four years.

I would also like to thank my family, in particular my parents Mary and Tommy who instilled in me a strong work ethic and taught me that the only way to achieve something is through persistence and hard work. Your encouragement and support both towards and during my education has been endless and is something I will be always be very grateful for.

Finally, a word of gratitude to Emma-Louise; you always provided a listening ear and you were a constant source of advice, support, encouragement, humour and most of all, love. I have no doubt we will look back on this journey in many years to come with fond memories.
Abstract

The successful integration of automatic milking (AM) and grazing has resulted in AM becoming a feasible alternative to conventional milking (CM) in pasture-based systems. The objective of this thesis was to establish (i) the social, environmental and economic effects of adopting AM technology and (ii) the factors affecting cow traffic, which once the AM is adopted, can also impact on the sustainability of AM. A theme across this thesis is the examination of AM in the context of a seasonal pasture-based milk production system. Electricity and water meters were installed on seven AM farms. Milking and livestock/miscellaneous processes were the largest consumers of electricity and water, respectively. Labour audits were conducted on seven and 10 AM and CM farms, respectively, and showed that there was a 36% reduction in labour with AM. A stochastic budgetary simulation model was used to establish the economic consequence of investing in an AM system relative to CM systems. AM technologies were less profitable than CM parlours of medium specification, but were as profitable as CM parlours of high specification. From a review of the literature knowledge gaps concerning (i) the effect of supplementation level and stage of lactation and (ii) suitability of breeds to AM were identified as areas pertinent to pasture-based systems. Low and high concentrate supplement levels were implemented. In late lactation, the high concentrate treatment had a greater milk yield, and a shorter milking interval and return time/visit. In a breed experiment, there were no differences between Holstein-Friesian, Jersey x Holstein-Friesian and Norwegian Red x Holstein-Friesian for milking frequency or milk production, although differences existed with regard to cow traffic. Greatest AM utilisation may be achieved by a mixed breed herd rather than a single breed herd, due to the complementary milking pattern that existed between the breeds.
Chapter 1: General Introduction
The European Union (EU) milk quota regime curtailed potential dairy farm expansion and production increases for over 30 years on European dairy farms. The removal of this regime has presented Europe's dairy farmers with an unprecedented opportunity to increase milk production without restrictions for the first time in a generation. Early predications by Lips and Rieder (2005) suggested that Irish milk production could increase by 39%, while the Food Harvest 2020 report set a target of a 50% increase in milk production by 2020 (DAFM, 2010).

Positive energy for expansion at farm level will result in larger herd sizes, with average herd sizes in Ireland expected to increase from 60 cows in 2010 to 104 cows in 2025 (Teagasc, 2017). This will place a greater strain on available labour resources and require a greater emphasis on labour efficiency. Indeed, labour availability, both skilled and unskilled, is considered among the greatest challenges facing dairy farmers in expanding dairy industries (O'Brien et al., 2015). Anticipated expansion in the Irish dairy sector will see a requirement for an additional 6,000 full time employees at farm level to meet Food Wise 2025 targets (Teagasc, 2017). Furthermore, the cost of labour is one of the largest farm expenses incurred annually. With Irish farm accounting systems negligent with regard to the inclusion of owner operator labour costs, the inclusion of such costs by international competitors highlights the significance of labour costs on the farm business. In an analysis of the costs of milk production in 46 countries, Hemme et al. (2014) found that labour costs were second only to feed costs, while a similar outcome was realised in an analysis of farm financials from the seasonal pasture-based production systems of New Zealand (DairyNZ, 2016), similar to those operated in Ireland.
Dairy farming is labour intensive, with many tasks required to be conducted routinely and systematically each day of the year. Milk harvesting in a conventional herringbone/rotary parlour is one such labour intensive task, which takes place from once to thrice but mostly twice daily for up to 300 days of the year (Jago and Woolford, 2002). This is the most time consuming dairy task and accounts for up to 34% of total dairy labour input on pasture-based dairy farms (O'Donovan et al., 2008). Additional to this, it is a task which rarely occurs during normal business hours, which can make it a challenging task to attract and retain skilled labour (Tarrant and Armstrong, 2012). Therefore, dairy farming is not commonly considered an attractive industry (especially for younger generations or people not directly involved in the industry) because of the negative perception of the lifestyle associated with dairy farming (Lyons, 2013a). This, combined with the demand for additional labour will require innovation from Irish dairy farmers in order to combat skilled labour shortages and to improve labour efficiency levels.

Innovation is defined as the development of new methods of working or establishment of new management systems (Edison et al., 2013). Having been first commercialised in 1992, automatic milking (AM) systems are now gaining in popularity with an estimated 10,000 (de Koning, 2011) to 25,000 farms (Harms and Bruckmaier, 2016) operating the system. The adoption of this milking system could be described as innovative, as the AM system undertakes the physical tasks of milking (cluster attachment and detachment) normally performed by the operator. This results in the establishment of a new method of management on farms, allowing the farmer to concentrate more on the management of the herd as opposed to performing physical milking tasks, as would be the case in conventional milking (CM) systems. Consequently, studies have identified a
reduction in labour requirement of between 10 and 30% (Sonck, 1995, Mathijs, 2004, Bijl et al., 2007) after the adoption of AM. Furthermore, farmers with AM cite improved health, better quality lifestyles and greater time flexibility as a result of the change to the AM system. Interestingly, while the reduction in labour and lifestyle benefits are well documented, a survey of Australian AM farmers identified staffing problems as one of the main reasons for investing in the technology (Kerrisk and Ravenhill, 2010).

However, until recently, many of these systems were operated in indoor cow management systems, with much of the knowledge surrounding the system operation emanating from research within these environments. The combination of AM and grazing was first reported by Greenall et al. (2004) and Jago et al. (2004) after successful integration in Australia and New Zealand, respectively. Further research has focused on the factors such as distance to pasture (Spörndly and Wredle, 2004), water (Spörndly and Wredle, 2005) and supplement location (Lyons et al., 2013d) and animal genotype (Nieman et al., 2015), in addition to grazing strategies to optimise the utilisation of the AM unit (Lyons et al., 2013c). However, the production systems within the aforementioned studies vary within the context of the production system which prevails within Ireland. Here, prevailing climatic conditions result in seasonal pasture growth. In order to maximise the cost effectiveness of pasture utilisation, and thus the proportion of grazed grass in the diet of the dairy cow, the adoption of a seasonal production system is necessary, with cows calving to match the onset of grass growth (Dillon et al., 2005). This results in a milk production pattern similar to the grass growth curve, with a peak trough ratio of 6:1, occurring in May and January, respectively (Quinlan et al., 2012).
Thus, having succeeded to integrate AM and pasture-based production systems, the challenge now exists to investigate the integration of AM systems into seasonal, low cost pasture-based production systems, to establish if the potential exists for AM to be a prudent solution to potential labour shortages on dairy farms in the future.

The overall objective of this thesis was twofold; i) to establish the environmental, social and economic sustainability of pasture-based farming with AM and ii) to establish the effects of supplementation level in the early and late lactation periods, and dairy cow breed on both production and cow traffic parameters in a pasture-based AM system. A common theme across this thesis is the examination of AM within the context of the seasonal, low cost pasture-based production system, where the focus is on minimising costs through the utilisation of high quality grazed pasture. Thus, this thesis aims to provide a greater understanding of the consequences of combining AM with the aforementioned production system, providing both farmers and industry alike with a significant body of information to allow informed decision making regarding the adoption of AM technology.

This thesis encloses a review of the literature, two study and two experimental chapters, along with a summary and general discussion. The results of the study and experimental chapters have been condensed into four independent standalone manuscripts, each with its own abstract, introduction, materials and methods, results, discussion and conclusion.

Chapter 2 reviews the literature in relation to the sustainability of AM and the factors associated with cow traffic in AM systems, while also providing an overview of the
Irish dairy industry. The review focuses on pasture-based systems, while also drawing on the findings of research from indoor production systems to help develop an understanding of the gaps in the knowledge.

The objective of Chapter 3 was to profile the daily and seasonal trends of electricity and water consumption on commercial pasture-based dairy farms milking with AM, while also identifying the contribution of key individual components to overall farm consumption efficiency.

With profitability an imperative for the survival of a dairy business, Chapter 4 aimed to establish what effect, if any, the adoption of AM technology had on the profitability of a dairy farm at two herd sizes, over a 10 year period, when compared with CM technology of varying levels of automation. This Chapter also describes the effect that adopting AM has on the labour requirements of commercial dairy farms.

With the seasonal nature of grass growth, the judicious use of concentrate supplements is a necessary component of pasture-based dairy systems, particularly in the early and late lactation periods. Thus, Chapter 5 aimed to determine how the provision of varying levels of concentrate supplement during the aforementioned lactation periods affects milk production and cow traffic in a pasture-based AM system.

The objective of Chapter 6 was to establish the suitability and compatibility of differing dairy cow breeds to pasture-based AM systems and the effect that may have on milk production, cow traffic and milking distribution within the system.
Finally, Chapter 7 encompasses a summary and general discussion on the findings of the analysis and studies included in this thesis, while also outlining the potential areas for future research.
Chapter 2: Literature review
2.1 Introduction

The purpose of this chapter is to review the available literature on the impact of automatic milking (AM) with regard to the sustainability of the system and the biological factors influencing system performance. This review will focus on (i) social, environmental and economic effects of adopting the technology and (ii) the factors affecting cow traffic which can also impact on the sustainability of the system.

2.2 The dairy industry in Ireland

2.2.1 General industry description

The Irish agri-food and drink sector accounts for 7.6% of Ireland’s economy-wide gross value added, 10.7% of Ireland’s exports and 8.4% of total employment (Bord Bia, 2017a). With over 90% Ireland’s dairy produce exported to ~130 countries globally, the dairy sector makes a significant contribution to these statistics. Dairy exports account for 31% of Irish agri-food and drink exports, with the value of these exports worth €3.38 billion to the economy (Bord Bia, 2017b).

At producer level, the Irish dairy industry is comprised of 18,350 dairy farms and 1.35 million dairy cows, resulting in an average herd size of 76 cows (Teagasc, 2017). The Irish dairy sector has undergone significant changes in the last 30 years and has not been immune from the international trend of reducing farm numbers and increasing herd sizes. Despite the number of dairy farms decreasing from 80,000 and the average herd size increasing from 18 cows at the introduction of the EU milk quota regime in 1984 (Teagasc, 2015), the remaining dairy farms still exits under the structure of the family farm ethos.
With the abolition of EU milk quotas in 2015, it has been projected that by 2020 milk production in Ireland will increase by 50% from the 2007-2009 baseline to a target of 7.6 billion litres per annum (DAFM, 2010). Total milk production for 2016 was 6.67 billion litres, a 35% increase on the aforementioned baseline (Teagasc, 2017). This additional production, combined with the dependency on global markets may expose dairy farmers to international variations in supply and demand, leading to uncertain milk prices and increased milk price volatility (Lips and Rieder, 2005, Dillon et al., 2016).

Figure 2.1 Glanbia milk price 1999 to 2014 (LTO-International Milk Price Comparison).

Figure 2.1 illustrates how Irish milk prices have become increasingly volatile due to growing global production, increasing reliance on price sensitive developing markets and increased market turbulence, arising from fluctuating supply/demand conditions (LTO, 2013, 2015). In the decade prior to 2004, average annual milk price received by farmers was 30 cent/litre (c/l) with little inter-annual variation (+/-2 c/l). In contrast,
during the decade since 2004, average milk price was 31.2 c/l, but with much greater variation (+/-8 c/l; LTO, 2013 and 2015).

2.2.2 Production system overview

Ireland has a competitive advantage over many countries due to the ability to grow large quantities of pasture over a long growing season (Dillon et al., 2008). This long growing season is facilitated by a temperate climate. Pasture growth typically commences in February and increases rapidly to peak pasture growth of up to 100 kg DM/ha per day in May/June and subsequently decreases on a gradual basis during the summer and autumn, until growth almost ceases in December (Hurtado-Uria et al., 2013). Seasonal production systems, such as those operated in Ireland, New Zealand and Australia are established in such a manner as to maximise the utilisation potential of grazed pasture, through aligning the start of calving with onset of pasture growth (Dillon et al., 2005).

This seasonal production system is an appropriate strategy to combat the negative consequences of milk price volatility, due to its design to make the herd's feed demand as similar as possible to the pasture growth rate in each month of the year (Figure 2.2; Holmes et al., 2002). In comparison with mechanically harvested or purchased feeds, grazed grass provides a relatively inexpensive and uniquely nutritious feed source for milk production (Finneran et al., 2012). Maximising grass utilisation improves farm profit with each additional tonne of grazed grass utilised/ha increasing net profit/ha by €161 (Dillon, 2011). Furthermore, increasing the proportion of grazed grass in the diet of the dairy cow by 10% has been shown to reduce costs of production by 2.5c/l (Dillon et al., 2005). This has significance for dairy farm profitability, as farm economic analyses have demonstrated a lack of association between milk production and
operating profit (Silva-Villacorta et al., 2005, Ramsbottom et al., 2015); thus, it is not the system with the greatest milk production that is most profitable, but the system with a combination of high milk production and lowest costs (Ramsbottom et al., 2015). Furthermore, the reduced profitability of systems dependant on high inputs of concentrates relative to systems which rely on high quality grazed grass, particularly in periods of low milk price, has been well documented (McCarthy et al., 2007b, Patton et al., 2012, Ramsbottom et al., 2015).

Figure 2.2 The seasonal grazing system; cows are calved and dried off to ensure synchrony between herd demand and feed supply.
However, as the name “seasonal production system” suggests, the nature of grass growth is seasonal due to the prevailing climatic conditions, which leads to grass deficits in the early and late lactation periods (spring and autumn, respectively; Holmes et al., 2002). This, therefore, necessitates the judicious use of concentrate supplements during these periods, when grass growth levels are sub-optimal and not sufficient to meet herd demands (McEvoy et al., 2008). Not alone is supplementation used as a tool at these periods to extend the grazing rotation, it can also be used to ensure the cow is offered sufficient energy in the diet (McEvoy et al., 2008), as the dry matter intake (DMI) of the dairy cow is at its lowest in the early lactation period (Ingvartsen and Andersen, 2000). The reduced DMI can result in cows experiencing energy expenditure greater than energy intake, also known as negative energy balance (Berry et al., 2006). Kendrick et al. (1999) outlined how cows on diets of higher energy density returned to positive energy balance sooner than those on diets of lower energy density. Thus, prudent use of concentrate supplement ensures that cows maintain energy balance and increase total DMI of dairy cows in early lactation (Delaby et al., 2001, Bargo et al., 2003).

A pasture-based seasonal production system, such as the one outlined here, requires a cow with a unique set of characteristics such as the ability to achieve high milk solids output from grazed grass, high grass DM intake per kg of live weight, high milk solids per kg DM intake and efficient reproductive performance which allow the cow to calve every 365 days (Berry, 2015). Additionally, Berry (2015) highlighted the ability to walk long distances each day and achieve adequate nutritional status within a predominately exclusively grazing diet as key factors. The widespread use of Holstein-Friesian (HF) genetics to increase milk production potential (Harris and Kolver, 2001, Evans et al.,
2006b) has ultimately compromised the fertility of the global dairy herd (Harris and Kolver, 2001, Norman et al., 2009); a trait which is the cornerstone of all seasonal calving production systems. Furthermore, Kennedy et al. (2003) and Horan et al. (2006) outlined how HF cows may not fulfil their genetic potential in pasture-based systems, as when these cows are on diets consisting of pasture only, they cannot consume sufficient energy to meet their requirements (Kolver and Muller, 1998). This has led to the adoption of a “high durability” HF (high fertility and survival traits; (Horan et al., 2005, McCarthy et al., 2007b)) along with the increasing popularity of both Jersey and Norwegian Red sires on HF cows to produce crossbred progeny. These cows are highly compatible with grazing systems due to their ability to satisfy the unique set of characteristics outlined above for a seasonal production system (Auldist et al., 2007, Walsh et al., 2008, Prendiville et al., 2009).

2.2.3 Challenges facing Irish dairy farms

The removal of the EU milk quota regime has presented the Irish dairy sector with both opportunities and challenges. One such opportunity is the potential to increase the productivity of dairy farms due to the under-utilisation of land resources that currently exists (O'Donnell et al., 2008). This can be achieved through increasing grass production and utilisation, allowing the dairy farm to carry more cows. Teagasc (2017) estimate that by 2025 average herd size will have increased to 104 cows. However, this presents the challenge of sourcing suitable skilled labour, with estimates that an additional 6,000 full time equivalent (FTE) labour units will be required by 2025 (Teagasc, 2017), to facilitate herd expansion along with generational renewal of the existing dairy farmer population. The difficulty to attract and retain talented staff to work on dairy farms is not an issue unique to Ireland, and has become an increasing

Dairy farming is labour intensive, with many tasks required to be conducted routinely and systematically each day of the year. Milk harvesting in a conventional herringbone/rotary parlour is one such labour intensive task, which takes place from once to thrice but mostly twice daily for up to 300 days of the year (Jago and Woolford, 2002). This is the most time consuming dairy task and accounts for up to 34% of total dairy labour input on pasture-based dairy farms (O’Donovan et al., 2008).

Additional to this, it is a task which rarely occurs during normal business hours, which can make it a challenging task to attract and retain skilled labour for (Tarrant and Armstrong, 2012). Therefore, dairy farming is not commonly considered an attractive career prospect to younger generations and people not directly involved in the industry due to negative perceptions of the associated lifestyle (Lyons, 2013a). However,

Figure 2.3 Breakdown tasks on with a CM farm as a proportion of total labour input associated with the dairy enterprise (O’Donovan et al., 2008).
technology can help to alleviate the intensity of such a task, reduce the labour requirement and may even help to attract new people into the industry (Lyons, 2013a). Many technologies exist to assist with harvesting milk in conventional milking (CM) parlours such as automatic cluster removers, automatic drafting and automatic plant washing (Edwards et al., 2015). While these technologies may provide milking operators with enhanced comfort and reduced fatigue (Tarrant and Armstrong, 2012) along with leading to a more structured milking routine (Ohnstad et al., 2012), they still necessitate the presence of a labour unit(s) at specific times each day, and in no way mitigate the unsociable working hours associated with the task.

Automatic milking systems, which fully automate the milk harvesting process without the need for human intervention, are one technology that has the potential to address both working conditions and labour requirements of dairy producers (Jago and Woolford, 2002). While the technology was initially adopted within indoor/restricted grazing production systems, its integration with pasture-based production systems in New Zealand and Australia has led to the possibility of AM systems becoming a feasible alternative to CM in such production systems (Greenall et al., 2004, Jago et al., 2004). With approximately 300 pasture-based Irish farms harvesting milk automatically by early 2017, the interest in the technology is increasing, as AM is a potential solution to overcome the shortage of skilled labour and increased labour demand associated with increasing herd size, by allowing more animals to be managed by existing labour (Edwards et al., 2015).
2.3 Automatic milking

2.3.1 Background to automatic milking

Many years of research and development to establish a device to milk cows without human intervention culminated with the launch of the first commercial AM unit in 1992 in the Netherlands. Since then between 10,000 (de Koning, 2011) and 25,000 (Harms and Bruckmaier, 2016) farms have adopted the technology. The most common AM unit is the “single box/unit” configuration. This formation sees one cow in the milking crate at a time, where she is milked by a robotic arm which performs tasks such as cup attachment and removal, and teat disinfecting post milking. These single box configurations can accommodate approximately 70 cows milking twice daily, resulting in the machine conducting 140 milkings each day (Lyons, 2013a). Given the current and expected average herd size in Ireland (Teagasc, 2017), it is not surprising that the single box configuration is the AM unit of choice for those who adopt the technology.

The fundamental difference between traditional and AM system milk harvesting methods is that AM relies on cows using the machine throughout the day and night to achieve sufficient cow throughput (Jago and Woolford, 2002). Consequently, milking can occur at any time, day or night, and is distributed over a 24 hour period, rather than occurring in batch fashion (Jago and Woolford, 2002). As milking can occur during each hour of the day, cows are not manually herded to the milking unit, but instead are trained to traffic voluntarily under their own initiative (Lyons, 2013a). As cows prioritise feeding over milking when given the option, feed is normally used as the primary incentive to attract cows to the milking unit (Prescott, 1995, Prescott et al., 1998). To compensate for the reduced human presence at the milking of each individual
cow, the capture of data with sensors is necessary to allow the operator to identify and subsequently act upon any changes in milking performance or milk quality (Lopez-Benavides et al., 2006).

Greater uptake and adoption rates of AM have occurred on farms that are smaller in size, often family owned and operated, where suitably skilled labour is difficult to source and expensive when it can be sourced (Svennersten-Sjaunja and Pettersson, 2008). Furthermore, they have primarily been integrated in systems with high producing cows and in regions which receive a high milk price (Svennersten-Sjaunja and Pettersson, 2008). Until recently the majority of AM systems have been installed in combination with indoor/restricted grazing production systems, in northern Europe, in countries such as Denmark, Sweden and The Netherlands. However, an increasing interest in grazing in the northern European countries, in combination with difficulty sourcing suitable skilled labour in countries such as Australia and New Zealand led to the integration of grazing and AM in the early 2000’s.

2.3.2 Automatic milking in combination with grazing

The combination of AM and grazing was first reported in the early 2000’s in Australia and New Zealand by Greenall et al. (2004) and Jago et al. (2004), respectively. These installations were based upon the principal of providing two periods of pasture allocations (day and night), with the prospect of receiving a new allocation of grazed pasture, the primary incentive for the dairy cow to traffic to the milking yard. In pasture-based AM systems, it is widely recognised that milk production and milking frequencies are lower and milkings are distributed less evenly than in an indoor AM system (Davis et al., 2005, Garcia and Fulkerson, 2005, John et al., 2016). While
pasture production systems are lower input and hence, lower output systems than confinement systems where cows are fed a total mixed ration diet (Davis et al., 2005), the reduced milking performance may have partly been attributed to the number of pasture allocations. Lyons et al. (2013c) reported that two allocations of pasture led to cows having long periods away from the milking yard, thus requiring fetching due to extended milking intervals. Furthermore, as large numbers of cows were manually fetched to the milking yard at once, these cows were subject to substantial waiting times in the pre-milking yard, as only one cow could be milked at a time. This led Lyons et al. (2013c) to investigate the impact of offering three allocations of grass during the 24 hour period. This provided cows with an additional incentive to traffic to the milking yard each day and resulted in a significantly reduced milking interval and increased milking frequency and AM system utilisation. This, therefore, increased the compatibility and improved the management of AM in pasture-based systems, with Clark et al. (2016) demonstrating no difference between pasture utilisation in AM and CM systems on an Australian research farm.

Milk produced from grazed pasture can now command a premium price, with the largest milk processor in the Netherlands, Friesland Campina, offering milk producers a price incentive to increase the time cows spend at grass (Reijs et al., 2013). While only 10% of global milk production is produced from pasture (Steinfeld and Mäki-Hokkonen, 1995), there is an increasing interest in grazing due to the improved milk quality (O’Callaghan et al., 2016) and animal health and welfare (Thomsen et al., 2007). This can create potential opportunities for new markets for dairy produce, as the green image associated with cows grazing pasture continues to appeal to increasingly discerning consumers. While the time required at pasture under the Friesland Campina scheme
only represents 25% of the day for 120 days of the year (Reijs et al., 2013), it has consequences for dairy farmers in countries such as the Netherlands where AM is widely adopted. These consequences include a possible reduction in milk output as a result of a potential lack of knowledge with regard to grassland management, particularly where grazing has not been practiced previously and the potential for reduced AM utilisation due to the requirement for cows to traffic away from the barn to pasture. This, in addition to increasing labour shortages, means that there is an increasing need to further investigate the integration of AM in pasture-based systems.

2.4 Factors associated with AM sustainability

Sustainable agriculture is defined as “the productive, competitive and efficient production of safe agricultural products, while protecting and improving the natural environment and the socio-economic conditions of farmers and local communities” (Bord Bia, 2013). Thus, sustainability encompasses three key areas, namely the social system, the environment and the economy. These are usually referred to as pillars. Here, the factors associated with AM sustainability under each of these three pillars are reviewed.

2.4.1 Social sustainability

A fundamental difference between AM and CM is that the manual tasks associated with CM, such as teat preparation, cup attachment and removal, and teat disinfection post milking are automated, thus not requiring the presence of a milking operator. This has the potential to impact on the social sustainability of dairy farming on a number of levels. Relative to CM, the milking process in AM is consistent and the milking routines are predictable for the cows, which are prerequisites for successful milking
This eliminates any variability which may exist between operators on a CM farm with regard to milking routine and ability to identify udder health issues, as CM systems are reliant on visual observation by the milker to detect udder health issues (Lopez-Benavides et al., 2006). Traditionally, AM systems have relied on the in-line milk detection sensors to identify changes in the electrical conductivity of milk (Woolford et al., 1998). However, Jacobs et al. (2012) identified that by combing the data from all of the sensors now available with AM (e.g. somatic cell count, electrical conductivity, milk colour, and expected milk yield) it may be possible to detect the stage of progression of a mastitis infection within a given quarter. This may allow the farmer to be more sensitive to potential mastitis problems, thus allowing earlier intervention and subsequently improved animal health relative to what would be possible in a CM system (Steeneveld et al., 2010). Furthermore, the fact that milking occurs on an individual quarter basis with an AM system should reduce the likelihood of over-milking which could occur as a result from one slow quarter in a CM system (CM occurs at the udder level), thus reducing the incidences of teat end trauma (Hillerton et al., 2004). Additionally, compared with cows milked in CM parlours, cows in an AM system have more freedom to control their daily activities and rhythms (Jacobs et al., 2012). This freedom and the potential animal health benefits associated with the use of sensors for earlier detection and subsequently, prevention of illness are aspects of AM which may help to improve the social sustainability of dairy farming, creating a more acceptable and appealing image to the consumer.

Undoubtedly however, the greatest difference in social sustainability between AM and CM systems is both the reduction in and change to on-farm labour input associated with AM adoption, as capital is substituted for labour (Steeneveld et al., 2012). Many studies
have attempted to quantify the change in labour associated with AM adoption, with mixed results. These studies are summarised in Table 2.1. Some studies have quantified the change in milking labour only, with Sonck (1995) recording a 56% reduction, while others have focused on the effect that AM has on total farm labour input (Mathijs, 2004, Bijl et al., 2007, Steeneveld et al., 2012) with an average of a 20% reduction recorded. This reduction in labour is the reason most cited by farmers for adopting AM technology (Hogeveen et al., 2004, Mathijs, 2004).
Table 2.1 Summary of the change in labour associated with the use of automatic milking (AM) systems compared to conventional milking (CM) as identified by seven studies in six countries

<table>
<thead>
<tr>
<th>Study</th>
<th>Country</th>
<th>Production system</th>
<th>Data source</th>
<th>Measurement method</th>
<th>% Labour change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dijkhuizen et al. (1997)</td>
<td>United States/Netherlands</td>
<td>Confinement</td>
<td>Assumption</td>
<td>-</td>
<td>-68$^6$</td>
</tr>
<tr>
<td>Rotz et al. (2003)</td>
<td>United States</td>
<td>Confinement</td>
<td>Assumption</td>
<td>-</td>
<td>-33/-50$^6$</td>
</tr>
<tr>
<td>Mathijs (2004)</td>
<td>Germany</td>
<td>Mixed$^3$</td>
<td>Commercial$^4$</td>
<td>Survey</td>
<td>-23</td>
</tr>
<tr>
<td>Jago et al. (2006b)</td>
<td>New Zealand</td>
<td>Pasture-based</td>
<td>Research$^5$</td>
<td>Audit/Assumption</td>
<td>-25</td>
</tr>
<tr>
<td>Bijl et al. (2007)</td>
<td>Netherlands</td>
<td>Confinement</td>
<td>Commercial$^4$</td>
<td>Survey</td>
<td>-29</td>
</tr>
<tr>
<td>Steeneveld et al. (2012)</td>
<td>Netherlands</td>
<td>Confinement</td>
<td>Commercial$^4$</td>
<td>Survey</td>
<td>0</td>
</tr>
</tbody>
</table>

1Data source = Refers to the source from which the data was obtained
2Measurement method = Refers to the method used to obtain the data
3Mixed = System was confinement with varied levels of grazing
4Commercial farm
5Research farm
6Refers to milking related labour only
With the exception of Steeneveld et al. (2012), all studies which quantified the labour change associated with AM are in agreement that AM reduces labour input. However, there is a substantial variation in the findings with reductions in total farm labour, varying from 11.5% in Belgium (Mathijs, 2004) to 29% in the Netherlands (Bijl et al., 2007). Furthermore, not alone is there variation between studies, but also within countries with Mathijs (2004) reporting labour saving of 18% in the Netherlands; 10% less than those reported by Bijl et al. (2007). The variation may be caused by the method of data collection, with the studies to date relying predominantly on the use of once-off retrospective surveys where farmers were asked to quantify the percentage their labour change, as was the case in the study of Mathijs (2004). Bijl et al. (2007) used farm accounts from both AM and CM farms, where farmers quantified the number of FTE's working on their farms. Interestingly, using this method Bijl et al. (2007) reported how AM farms carried more cows and produced more milk per FTE than on CM farms. However, this method is not without fault, as when comparing the number of FTE's between AM and CM farms, Steeneveld et al. (2012) found no difference, thus indicting no reduction in labour with the adoption of AM. However, the authors of that study acknowledged that as the FTE's were recorded by the farmers themselves, it is possible that these farmers may record a FTE regardless of the hours worked each year, which may be reduced with the AM system but still considered full time by the farmer. Thus, the need exits to obtain field data through continuous on-farm audits to establish an accurate indication of the reduction in labour associated with AM, particularly within the pasture-based production system.

The labour associated with AM systems includes visual monitoring of milking and cow data, cleaning, and checking of attention lists on AM systems (Steeneveld et al., 2012).
This leads to greater time flexibility (Hogeveen et al., 2004) as these tasks are not required to be conducted at specific, often unsociable times of the day, as is the case with CM (Tarrant and Armstrong, 2012). This increased level of flexibility is the second most prevalent reason cited by farmers for adopting AM (Hogeveen et al., 2004, Mathijs, 2004). The reduction in physical labour demand and the increase in time flexibility represents an enhanced social aspect to dairy farming which results in farmers citing both improved lifestyle, and physical and mental health (Mathijs, 2004). However, while these are positive aspects associated with AM, the continuous nature of AM operation (24 hour milking) represents a possible social negative associated with the system. When establishing the motivations of Dutch dairy farms for not investing in an AM system, Hogeveen et al. (2004) outlined that the second most influential factor was the prospect of being on standby for 24 hours of the day, due to the potential for failures to occur at any time of the day, thus creating a dependency. When interviewed regarding their adoption of AM, some of the Norwegian farmers referenced how the increased flexibility had come at a price as they considered being on call a dominating disadvantage (Hansen, 2015). However, creative solutions such as collaboration with a neighbouring AM farm to overcome this disadvantage had been found (Hansen, 2015). Nonetheless, when considering AM adoption both positive and negative social factors should be considered in synchrony.

2.4.2 Environmental Sustainability

There is an increasing challenge to produce animal-source food in a resource efficient manner due to the greater demand arising from growing global population, rising incomes and urbanisation (FAO, 2009). However, this is only one challenge facing global agriculture, as, simultaneously, it must preserve the world’s environment and
natural resources (McCarthy et al., 2015). This process of producing more food, while reducing the environmental impact of agricultural production systems, has become a global challenge and requires what has been referred to as sustainable intensification (Pretty, 1997; McCarthy et al., 2015). It is now accepted that greenhouse gas emissions (GHG; also referred to as the carbon footprint) are contributing to global climate change (Yan et al., 2013), with the global dairy sector estimated to contribute 2.7% of GHG (Gerber et al., 2010). In an Irish context, McGettigan et al. (2010) highlighted how agriculture is the largest contributor of GHG emissions with 26% of the total, while O’Brien et al. (2016) documented the main milk GHG sources as enteric methane (46%), followed by emissions from inorganic fertilisers (16%), manure (16%) and concentrate feedstuffs (8%).

With the removal of the EU milk quota regime, farmers may decide to adopt alternative production strategies such as confinement systems using a total mixed ration diet, particularly where land availability is a major constraint (O’Brien et al., 2012c). However, from an environmental viewpoint this may be detrimental, as confinement systems have a higher carbon footprint, and subsequently greater environmental impact, due to the greater use of concentrate feeds and longer manure storage periods (Leip et al., 2010; O’Brien et al., 2012c; O’Brien et al., 2014). Despite the lower carbon footprint of pasture-based dairy farms, significant room for further carbon footprint reductions exist, with Yan et al. (2013) and O’Brien et al. (2016) highlighting increased milk production without increasing concentrate feeding, increasing the genetic merit of the herd and optimising fertiliser nitrogen use with effective sward management of white clover as strategies for further mitigation. However, increasing concern exists for grazing systems with regard to nitrogen use efficiency and as to the effect of intensive
farming on potential nitrogen losses to ground and surface waters (McCarthy et al., 2015). Interestingly, Ryan et al. (2012) demonstrated how increasing the grazing season length resulted in a 5% increase in nitrogen use efficiency, the consequences of which are favourable as the costs associated with nitrogen inputs increase.

Studies in the literature comparing the environmental sustainability of AM and CM systems are scant, with only Oudshoorn et al. (2012) drawing comparison between the two on organic farms. Findings from that study indicated that no differences existed between the two milking systems examined, despite shorter daily grazing time and a lower proportion of grazed grass in the dairy cows diet. While not measured in the study of Oudshoorn et al. (2012), one area where environmental differences could be expected to occur between AM and CM systems are in terms of the water and electricity consumption due the increased magnitude of electronics and moving parts associated with AM. This is noteworthy, particularly as there is an increasing recognition of the tension between livestock produced food and water use (Ridoutt et al., 2014, Murphy et al., 2017), while electricity consumption has been shown to represent 25% of total energy use on pasture-based dairy farms in New Zealand (Wells, 2001). Thus, understanding the distribution of and demands on water and electricity for livestock production are of particular importance.

Studies carried out to date to develop this understanding have focused on CM systems. Murphy et al. (2014 and 2017) and Higham et al. (2017) have profiled total water consumption on non-irrigated pasture-based dairy farms. Murphy et al. (2014) outlined that 6.4 litres of water were required to produce a litre of milk, with the pre-cooling of milk the largest milking shed consumer. This is less than the 11.7 and 9 litres recorded
by Ridoutt et al. (2010) and Higham et al. (2017), respectively; however, substantial leakage (26%) was identified in the water pipe network on the farms of the latter study. Higham et al. (2017) also outlined the seasonal trends in water consumption with all water consumption reaching peak demand in the summer months and recording its lowest demand in the winter months.

Upton et al. (2013) quantified total electricity consumption and the individual components contributing to the total consumption on a seasonal production pasture-based dairy farm. Results from that study outlined how the production of one litre of milk required 42Wh of electricity costing 0.51 cents/litre. Milk cooling and water heating were the largest users of electricity. This study also demonstrated both the seasonal and daily trends in consumption, with the seasonal trends following the milk supply curve, while the daily trends were centred on twice daily milk harvesting periods.

Studies conducted on AM systems have been lacking in a whole farm approach, instead focusing on the consumption (both electricity and water) of the AM unit (Artmann and Bohlsen, 2000) and the differences in consumption of varying AM unit brands (Jensen, 2009). Artmann and Bohlsen (2000) outlined that the vacuum pump was the main contributor to AM unit electricity consumption. However, as the compression of air is required for the opening and closing of AM entry and exits, the consumption of electricity associated with the air compressor was included in the study of Calcante et al. (2016). This inclusion highlighted the air compressor as a significant consumer of electricity in the milking process. However, this study was unable to provide a breakdown of the consumption within the AM unit, therefore making comparison with
Artmann and Bohlsen (2000) difficult. The study of Upton and O'Brien (2013) recorded the usage of the individual electricity consuming components in the milking shed, with the water heating process demonstrated as the largest consumer of electricity, followed by the air compressor, milk cooling and the vacuum pump. However, it should be noted that the water heating process included not just the heating of water for washing the AM unit, but also water heating for washing of the milk storage tank. This, therefore, highlights the importance of developing an understanding of total farm electricity consumption, as it provides a more accurate representation to help establish future strategies that may increase the sustainability of the AM system.

The study of Upton and O'Brien (2013) also provided a comparison of electricity consumption in an AM shed and CM shed on a seasonal calving pasture-based research farm during the mid-lactation period. This study reported a 79% increase in electricity consumption with AM (47 Wh/L v 84 Wh/L), primarily caused by the consumption associated with more frequent hot-washing of the AM unit and the air compressor. Furthermore, applying day and night rate tariffs to ascertain a monetary value resulted in an increase of 58% in electricity costs. While the authors acknowledge that the results obtained may be greater than the performance on commercial farms due to (i) extended milking times in CM parlour due to the conducting of experimental procedures and (ii) the AM system was in its first years leading to reduced output, the results still provide a good indication with regard to the tendency for increased consumption with AM. Furthermore, both Bijl et al. (2007) and Steeneveld et al. (2012) highlighted how energy costs were higher on Dutch AM farms compared with CM farms.
Thus, reducing the increased electricity consumption and costs is going to be paramount to both environmental and AM sustainability. Upton et al. (2015a) demonstrated how, due to the sinusoidal trend of electricity consumption, CM systems were not compatible with renewable technologies. Furthermore, Upton et al. (2013) highlighted that up to 38% of electricity was used during the off peak period on CM farms, resulting in the day and night tariff pricing structure being the most economical for CM farms (Upton et al., 2015b). Studies conducted to date on AM have failed to report the trends in both electricity and water consumption, which due to the continuous operational nature of AM may differ from those outlined in the literature for CM systems. This may have an impact on the strategies chosen to increase the competitiveness of AM. Additionally, understanding the trends in water consumption is important for farm planning, to allow for sizing of infrastructure, such as water pumping and storage systems. For instance, where the peak water demand exceeds the flow rate from the supply source, storage is required so the demand from the farm can be met without exceeding the rechargeable rate of the groundwater source (Murphy et al., 2014). However, in the absence of such information, it is not possible for AM adopters to make informed decisions to help improve the competitiveness and sustainability of their farms.

2.4.3 Economic Sustainability

When evaluating investment in milking technology, it is important to consider the effect such an investment will have on the long term profitability of the farm business, given all of the considerations involved. Profitability and economic reasons are the most cited reasons by farmers for not investing in technology (Hogeveen et al., 2004, Moyes et al., 2014, Steeneveld and Hogeveen, 2015). Thus, it is not surprising that many studies have attempted to examine changes in the profitability of the dairy farm as affected by the
adoption of an AM system, taking cognisance of the many permutations of key performance indicators from the differing dairy farm systems. Simulation models have been widely used for this process (Dijkhuizen et al., 1997, Cooper and Parsons, 1999, Rotz et al., 2003, Jago et al., 2006b), while others have examined the business profitability from farm accounts of AM farms and compared those of AM and CM farms over a 1- to 3-yr period (Bijl et al., 2007, Steeneveld et al., 2012). Additionally, the decision regarding investment in AM can be analysed as a real options problem, whereby the uncertainty and irreversibility associated with an investment is taken into consideration (Engel and Hyde, 2003, Floridi et al., 2013).

Irrespective of the method of analysis used, the majority of studies are in agreement that the adoption of AM does not increase the profitability of the dairy farm (Dijkhuizen et al., 1997, Rotz et al., 2003, Bijl et al., 2007, Steeneveld et al., 2015), despite reduced labour requirements, with a number of reasons cited. Firstly, AM is a capital intensive technology, which leads to greater levels of depreciation (Steeneveld et al., 2012), and where finance to fund AM has been borrowed, greater interest rates (Bijl et al., 2007). Bijl et al. (2007) highlighted, how on Dutch dairy farms, depreciation and interest was €13,000 greater with AM. Steeneveld et al. (2015) also demonstrated how increased depreciation and interest led to reduced profitability, despite increased milk revenues. Secondly, this increased depreciation relative to CM system is added to by the major source of uncertainty with AM; that being the useful life of the AM technology (Engel and Hyde, 2003). Due to improvements in AM technology since commercialisation and the relative recent adoption of the system, little information is available on the economic lifespan of an AM unit (Bijl et al., 2007, Steeneveld et al., 2012). This has led studies to depreciate AM over a shorter period of time than CM, with Dijkhuizen et al. (1997)
doing so over 7 years compared with 12 for CM. However, the shorter lifespan of AM may be compensated with higher maintenance costs as a result a greater replacement rate of parts (Bijl et al., 2007); however, information on the maintenance cost of AM is limited. Bijl et al. (2007) reported that Dutch AM dairy farms recorded greater maintenance costs than CM farms, with the authors noting that this was not unexpected due to the greater complexity of an AM unit as a result of more electronics and precision mechanics. Finally, as noted in the previous section, AM energy running costs have been shown to be higher than CM, which also contributes to the negative economic outcomes observed in the literature towards AM.

The combination of these factors led Jago et al. (2006b) to report that it costs 27% more to produce a kg of milk solids in comparison with a CM rotary system. Furthermore, while the studies outlined above have found reduced profitability with AM, many have modelled scenarios required to make AM as profitable as CM. Reduced capital costs have been outlined as a method to improve AM competitiveness. Studies have highlighted how the purchase price of the AM system must reduce by 20% (Rotz et al., 2003) for a confinement system, up to 70% (Jago et al., 2006b) for a pasture-based system. This would in turn help to reduce the depreciation associated with the system. Rotz et al. (2003) also demonstrated how AM would be a feasible alternative to CM if the cost of milking labour in the US were to double, while Jago et al. (2006b) outlined how the number of cows going through their AM (90 cows) would have to double. Alternatively, Jago et al. (2006b) proposed a 25% decrease in capital costs, a ratio of 112 cows/AM unit (with no negative milk production effects) and a 10% increase in the cost of milking labour as a means of making AM economically viable. Both Cooper and Parsons (1999) and Rotz et al. (2003) also highlighted the need for an appropriate ratio
of cows: AM unit, with Rotz et al. (2003) reporting the greatest AM profit when 60 cows/AM unit were milked with moderate milk production. Ratios below this may lead to underutilisation of AM, while above this have negative consequences for animal performance. Additionally, the same study outline how at 100-120 cow herd sizes, two single stall AM units were as profitable as a high specification CM parlour, due to the lower investment in a multi-stall AM system. However, these findings are in the context of a confinement production system where cows were achieving two and a half to three milkings/day.

While the studies outlined above did not report increased profitability with AM, they do not directly take into account the effect the variability of returns (uncertainty) and sunk costs (irreversibility) associated with investment may have on the decision to invest in AM (Engel and Hyde, 2003). This is known as real options analysis. When using real options analysis over a 15 year lifespan of a CM parlour, Engel and Hyde (2003) documented that the decision to replace an operational CM parlour and invest in AM would be economically justified once the parlour was five years or older. At this point the uncertainty was reduced as the likelihood of the AM system outlasting the CM parlour and being operational in year 15 was increased.

Defining how economical sustainable a system is, is dependent upon the desired metric used by an individual to quantify economic sustainability. While profitability is crucial for the survivability of a business, profitability alone should not be the sole focus of the business. While AM may be less profitable than CM, the social benefits obtained from adopting a technology such as AM may in fact outweigh the loss of profit. This was evident in the study of Hogeveen et al. (2004) where reduced labour was cited as primary reason for AM adoption. Thus, for these farms profit per hour of labour
becomes an important metric. Interestingly, although AM farms in Belgium and the Netherlands reported reduced income relative to CM, when expressed per hour of labour input income exceeded that of the CM farms (Wauters and Mathijs, 2004). Similar findings were reported by Bijl et al. (2007). This indicates that for many farmers the decision to adopt AM is more than just an economic decision; it is a socio-economic decision (Hogeveen et al., 2004, Mathijs, 2004, Bijl et al., 2007).

With the exception of Jago et al. (2006b), all of the AM economic analyses present in the literature are conducted in the context of confinement production systems, where calving and milk production patterns differ substantially from those found on a typical seasonal calving pasture-based system. Furthermore, the study of Jago et al. (2006b) was conducted for the typical New Zealand dairy herd (450 cows) and using a standard conventional rotary. Thus, it is imperative to quantify the economic consequences of AM adoption for the typical Irish dairy herd, in a low input seasonal milk production system, across milking technologies of varying specification.

2.5 Factors affecting voluntary cow traffic in an AM systems

Voluntary cow traffic is the foundation on which successful AM systems operate. Cow traffic is described as voluntary if the cows travel unassisted throughout the farm system in search of rewards (e.g. feed) for doing so (Lyons et al., 2014b). Without voluntary traffic, milking events will not be distributed evenly throughout the day and failure to achieve this voluntary traffic and distributed milking regime daily may have a negative effect on the uptake and adoption of AM technology at farm level (Lyons et al., 2013d). Furthermore, Lyons et al. (2013d) identified the time it takes for a cow to traffic to the
dairy facility from pasture as one of the most influential cow traffic variables. Here, potential factors which may influence voluntary cow traffic in an AM system are reviewed.

2.5.1 Pasture allocation

Pasture allocation can be interpreted in one of two ways. Firstly, it can refer to the quantity of pasture allocated to the herd, expressed as kg DM/cow per day or expressed as a proportion of the total diet. Grazing management within a CM system has dual objectives; (i) to allocate enough herbage to ensure the herd is adequately fed, and (ii) restrict the pasture allocation to ensure high pasture utilisation (Peyraud and Delagarde, 2013). The grazing objectives within a pasture-based AM system are threefold; they include the two objectives as per the CM system, along with ensuring that optimum pasture is allocated to ensure a consistent flow of cow traffic. The quantity of feed offered is more pertinent to pasture-based AM system compared with indoor systems due to the proximity (or lack of in the case of pasture-based systems) to the milking unit (Kerrisk, 2009, John et al., 2016). However, when investigating the effect of variable pasture allocation (kg DM/cow per day) on milking frequency, Dickeson et al. (2008) did not find any effect.

Lyons et al. (2013b) demonstrated a relationship between the proportion of grazed pasture in the dairy cow diet and cow traffic, with milking interval, and subsequently return time from pasture increasing as the proportion of pasture in the diet increased. For every 5 kg DM/cow increase in pasture allowance above 10 kg DM/cow, there was a 10-15 minute increase in milking interval. This is not unexpected, as feed is the main incentive for cows to traffic to the milking yard (Prescott et al., 1998); thus, the greater
the proportion of pasture in the diet, the greater the amount of time it will take cows to harvest that pasture, increasing their time away from the milking yard. However, unexpectedly, as the proportion of pasture exceeded 90% of the total diet milking interval decreased (Lyons et al., 2013b). With only 1% of total milkings occurring under this dietary circumstance, no apparent causes for such a trend were identified. However, there is significance here for a low input pasture-based system where for large parts of the season the cows diet is comprised in excess of 90% grazed pasture. It is possible that such a trend was observed as high quality grazed pasture is a less fibrous material than the forage components of a partial mixed ration, such as the one used as a supplementary feed by (Lyons et al., 2013b), thus increasing the rate of feed passage through the rumen (Mambrini et al., 1994). This would result in cows with a lower rumen fill (Kennedy et al., 2011), leaving them with a greater appetite; consequently, grazing behaviour would be altered due to this greater appetite resulting in the pasture allocation being consumed in a shorter period of time (Kennedy et al., 2009). Once the pasture was depleted, cows were incentivised to return to the milking unit to receive a fresh break.

Secondly, the term pasture allocation can also be used when referencing the number of sections of grass allocated to the herd in a 24 hour period (e.g. one to three allocations). In indoor AM systems, if pasture is offered to the herd, it is usually offered as one allocation during the day time with cows returning to the barn at night time (Ketelaar-de Lauwere et al., 2000, Lyons et al., 2014b). The first systems fully integrated with grazing adopted two pasture allocations, with allocation made available to the herd in the morning and the other late in the evening (Greenall et al., 2004, Jago et al., 2004). This system of two way grazing (2WG) has been shown to achieve levels of pasture
utilisation which are comparable with those of CM systems (Clark et al., 2016). However, this system of pasture allocation only provided cows with two daily incentives to traffic to the milking yard, resulting in the potential for long return times from pasture and extended milking intervals. A study from an indoor production system highlighted the influence of increasing feed provisions on improved cow traffic with a reduction in pre-milking yard waiting time/visit when feed was allocated six times daily versus twice daily (Oostra et al., 2005). In the context of a pasture-based system, this led Lyons et al. (2015) to conclude that the most effective way to reduce the extended milking intervals is to reduce the time cows are spending in any one given pasture allocation. Lyons et al. (2013c) proposed three-way grazing (3WG) as a potential alternative to the traditional 2WG commonly operated in pasture-based systems. Adopting 3WG led to a 31% reduction in milking interval, a 40% increase in milking frequency and a 20% increase in daily milk production (Lyons et al., 2013c). Three-way grazing also led to a reduction in return time from pasture, and reduced pre-milking yard waiting times (Lyons et al., 2013c). The improved cow traffic also led to a greater utilisation of the AM system. While increasing from two to three pasture allocations had a positive impact on cow traffic, Lyons et al. (2013c) concluded that it would be unlikely that an increase beyond three allocations per day could result in a worthwhile increase in cow traffic. This is due to the reduction in time that cows would be allowed to access a given pasture allocation, which would potentially limit the proportion of cows that gain access to the allocation. Thus, cow traffic could begin to be limited by cow time budget constraints.
2.5.2 *Pasture cover*

Pasture cover, alternatively known as pasture biomass, refers to the quantity of pasture in a defined area, expressed as kg DM/ha (Tunon, 2013). Pasture cover can also be expressed in terms of compressed sward height, with sward height increasing with pasture cover (O'Donovan et al., 2002). Lyons et al. (2014b) identified pasture cover as one of the main influences on cow traffic in a pasture-based system. High pre-grazing pasture-biomass (>3,000 kg DM/ha above ground level) have been shown to improve cow traffic, through reducing return time from pasture and subsequently, reducing milking interval (Lyons et al., 2013b). This is potentially a consequence of an increased bite mass associated with increased pasture biomass (Phillips, 2008). On the contrary, low pre-grazing pasture covers have been associated with reduced cow traffic, prolonging the time cows spent in a given pasture allocation and subsequently, increasing milking interval (Lyons et al., 2013b). Similar to the high pre-grazing pasture cover, this is likely a consequence of bite mass achieved by the grazing cow, with the lower pasture cover reducing the bite mass and increasing the time taken by cows to harvest the area of allocated pasture (Barrett et al., 2001, Phillips, 2008). While grazing high pre-grazing pasture covers (>3,000 kg DM/ha above ground level) had a positive impact on cow traffic, no information was provided by the aforementioned study on the pasture utilisation levels when grazing such covers. However, while it may be necessary to graze high-pasture covers at times of grass deficits, it is not advisable to do so as a strategy to improve cow traffic due to its negative impacts on milk production (McEvoy et al., 2009, Curran et al., 2010) and grass quality (Wims et al., 2010). Thus, when considering strategies to implement for cow traffic optimisation, pasture cover should not be considered in isolation and should be considered in the context of the whole farm system.
While it may be possible to avoid pre-grazing covers of an extreme nature, it will not be possible to avoid depleting pasture covers. Given the voluntary and almost continuous nature of cow traffic in an AM system, some cows will arrive at a given allocation when it has been grazed down to a low pasture-cover by the cows that accessed the allocation early. Those cows that arrive late may express differing behaviours which may impact on cow traffic (Lyons et al., 2014b). Ketelaar-de Lauwere et al. (2000) experienced an increase in cow traffic to the dairy as pasture height reduced, while Lyons et al. (2014a) reported that cows react to pasture biomass availability and would rather walk to the next pasture allocation than continue grazing at low pasture biomass. Again, while this may represent a positive in terms of reducing the time between visits to the milking yard, this may pose potential challenges to a pasture-based system in terms of pasture utilisation and subsequent pasture quality.

2.5.3 **Distance to pasture**

Given the competitive advantage that the pasture-based system provides for the Irish dairy industry, it is imperative to understand the relationship between distance to pasture and cow traffic. However, studies examining the effect of this where pasture forms almost 100% of the diet are limited. Lyons et al. (2013b) established that when cows had to travel distances in excess of 500 metres to access pasture, milking interval and return time from pasture were increased. In that study pasture comprised 57% of the diet, with the remainder made up of partial mixed ration and concentrates. The findings of this study are in agreement with that of Ketelaar-de Lauwere et al. (2000). Spörndly and Wredle (2004) indicated a reduction in milking frequency when cows had to travel 260 metres to the paddock entrance. Interestingly, in that study the distance to the furthest point in the paddock was up to 850 meters away which may have impacted on
the outcome. Similar to the study of Lyons et al. (2013b), Spörndly and Wredle (2004) made supplementary forage available in the barn. Contrary to these findings, both Greenall et al. (2004) and Woolford et al. (2004) described how cows travelled distances of 700 and 900 metres, respectively, while still achieving a milking frequency in the region of 2.5 milkings/cow per day. Distance to pasture is likely to be of greater relevance to larger herds, as these herds would be expected to walk 1-1.5 km one way to reach pasture (Lyons et al., 2014b). Taking into consideration the average herd size of an Irish dairy farm (76 cows; (Teagasc, 2017)), it is reasonable to assume that the effect of distance to pasture on cow traffic would be limited as, depending on farm layout, the frequency at which cows would be required to walk long distances would be curtailed due to the smaller size of the farm.

2.5.4 Climate

Previous studies have suggested that climatic conditions can impact on cow traffic, predominantly in regard to hot weather. Ketelaar-de Lauwere et al. (1999) found that in hot weather cows spent less time at pasture and more time indoors in the shade of the barn, concurring with the findings of Lessire et al. (2015) who found an increase in milking frequency with hot weather. However, contrary to these findings, Lessire et al. (2017) reported a reduction in visits to the milking yard during warmest periods of the day (1200 -1600 h), with visits moving to the evening 1600 - 0000 h. Thus, John et al. (2016) highlighted the need to establish suitable management strategies to maintain both cow traffic and cow health in periods of hot weather. However, the studies identifying the effect of weather conditions that are more prevalent in temperate regions (e.g. wind and rain) on cow traffic are limited. Both Ketelaar-de Lauwere et al. (1999) and Jago (2009) had similar experiences with such weather, indicating that it caused voluntary
cow traffic to slow down. However, the findings of Jago (2009) are of an anecdotal nature and therefore it can only be concluded that there is a need to establish the effect of wet weather on cow traffic, in particular the relationship between wet weather and the remaining pasture cover within a given pasture allocation.

2.5.5 Water availability

With lactating dairy cows drinking up to 72 litres of water per day (Higham et al., 2017), it is not surprising that that in addition to feed, water has been suggested as an incentive to encourage dairy cows to traffic back from pasture to the milking yard. Jago et al. (2005) analysed water consumption behaviour in a CM system and found although water consumption was condensed around milking session time, it could be an effective motivator for individual cows. When comparing cow traffic between treatments with access to water in the barn or in the barn and pasture, Sporndly and Wredle (2005) did not observe differences in cow traffic, milking frequency or milk production. Taking the temperature of the Australian climate into consideration (~30°C), Lyons et al. (2014b) suggested that by only providing water in the barn, it may compromise animal welfare. However, in more temperate conditions such as those experienced in Ireland where there can be considerable periods of rainfall, the use of water as an incentive to travel to the milking yard may not be effective. Morris et al. (2010) outlined how significant levels of rainfall can reduce water consumption by livestock by as much as 62%, as livestock have the ability to consume between 30 and 120 litres of water/day, with the level consumed varying for cows in pasture based systems due to the fluctuating DM content of grass (Higham et al., 2017). Thus, taking this variability into account, relying solely on water as an incentive to attract cows to the milking yard should not advised, although it could be used in combination with other incentives.
2.5.6 *Supplementation*

In CM pasture-based systems, supplementary feed is used prudently, to extend the grazing rotation, cover periods of pasture deficit and ensure sufficient DMI of early lactation cows (McEvoy et al., 2008). However, in a pasture-based AM system supplementation at the milking yard (in the form of total/partial mixed rations) or in the AM unit (in the form of concentrates) can also act as an incentive to entice cows to traffic voluntarily from the field to the AM unit (Salomonsson and Sporndly, 2000). However, the success of using supplements in enticing cows to AM unit has been mixed. Jago et al. (2007) investigated the effect of offering 1 kg of crushed barley/cow per day in the AM unit in a pasture-based system and found that although it did increase the visits to the selection unit, it did not result in an increased milking frequency. These findings were added to by the study of Lessire et al. (2017) who found that supplementing with 4 kg/cow per day as opposed to 2 kg/cow per day increased visits to the milking unit, but did not translate into more milkings. However, Scott et al. (2014) reported a reduction in pre-milking yard waiting times, along with a small increase in milking frequency with the provision of a low quantity of concentrates in the milking unit (~0.5 kg/cow per day). In confinement production systems, both Bach et al. (2007) and Halachmi et al. (2005) found no difference in milking frequency when offering 3 and 8 kg/cow per day and 1.2 and 7 kg/cow per day, respectively. However, providing supplementary feed, in the form of a partial mixed ration, external to the milking unit has been shown to influence cow traffic in a pasture-based system. Nieman et al. (2015) demonstrated how offering a partial mixed ration and pasture increased the average number of visits and milkings per day compared with offering pasture alone, with this effect more prominent in the high yielding HF herd. Furthermore, Lyons et al. (2013d) outlined that when offering forage as a supplement, the provision of that forage either
before or after milking impacts on cow traffic, with cows that were supplemented pre-milking returning from pasture more quickly. However, these cows spent more time feeding than the cows offered forage post milking, while also recording more time waiting in the pre-milking yard. This resulted in no difference in milking frequency and would indicate that feeding pre-milking reduces the motivation of the dairy cow to traffic through the milking yard.

2.5.7 Stage of lactation

Stage of lactation is widely recognised as a factor that has a significant impact on cow traffic. Jago et al. (2006c) demonstrated how cows in late lactation were less motivated to visit the milking yard than early lactation cows, with more late lactation cows requiring fetching than early lactation cows. Clark et al. (2014) also outlined how the number of gate passes recorded by HF cows reduced from early to mid-lactation, indicating reluctance to traffic to the milking yard voluntarily. These findings were given credence to by the study of Lyons et al. (2013b), where the proportion of extended intervals increased as stage of lactation progressed. Similar to Jago et al. (2006c), Lyons et al. (2013b) outlined how, with the same milking permission settings, milking interval increased from 12.5 hours in early lactation to 17.1 hours in late lactation (milking interval increased from 14.6 to 20.4 hours in the study of Jago et al. (2006c)). Interestingly, Lyons et al. (2015) described how late lactation cows had a higher probability of having an extended milking interval after being refused at the milking yard. However, both Lyons et al. (2013c) and Scott et al. (2014) described how, in a mixed herd of varying stage of lactation, early lactation cows were observed to have longer pre-milking yard waiting times, which may be a result of late lactation cows being more conditioned to the milking yard than early lactation cows. In a pasture-based
AM system where pasture allocations are the primary incentive for cows to traffic voluntarily, it is possible the milk yield reduction associated with late lactation reduces the appetite of the dairy cow, thus reducing the motivation to access fresh pasture, impacting negatively on cow traffic (Lyons et al., 2014b). Lyons et al. (2014b) outlined how it is important to understand how cows in different stages of lactation can be motivated in order to design protocols to manage cow traffic throughout lactation. This is of particular importance to a compact seasonal calving system, where all cows in the herd are at a similar stage of lactation, with periods such as late lactation having potential to result in a negative effect on cow traffic; thus, impacting on milking frequency and system utilisation.

2.5.8 Parity

Parity has been shown to influence cow traffic variables, with willingness to traffic voluntary around the grazing system decreasing as parity increases (Clark et al., 2014). However, upon reaching the milking yard, the primiparous animals (those who were more inclined to traffic around the system more voluntary) record longer waiting times in front of the AM unit (Donohue et al., 2010). This resulted in primiparous animals recording an 11% longer milking interval than multiparous animals in the study of Lyons et al. (2013b). Jacobs et al. (2012) outlined how the effect of parity could be linked to bodyweight, with the lightest animals, in this case the primiparous animals, waiting the longest. However, the provision of feed in the milking area has also been shown to have a positive effect on primiparous cow traffic. Lessire et al. (2017) demonstrated how primiparous cows trafficked to the milking robot more frequently, and subsequently, had a higher milking frequency when the level of concentrates offered was increased from 2 to 4 kg/cow per day. Additionally, Scott et al. (2014) also
found that the provision of concentrates also encouraged primiparous animals to traffic more quickly through the pre-milking yard. As described earlier, milking frequency decreases as stage of lactation increases; however, parity also has an influence on this, with the rate of milking frequency decline increasing as parity increases (Lovendahl and Chagunda, 2011, Pettersson et al., 2011).

2.5.9 Breed

The findings relating to the effect of breed in AM systems, in particular those breeds previously identified as being compatible within CM pasture-based systems, are scant. This led John et al. (2016) to question what breeds, or combinations of breeds, were best suited to pasture-based AM systems. Only Clark et al. (2014) has investigated the differences that exist between breeds with regard to cow traffic performance, while Nieman et al. (2015) examined the differences between strains of HF. Clark et al. (2014) compared HF and Illawara breeds milking in a non-experimental setting on an Australian research farm over a two year period. The Illawarra breed were found to record 9% more gate passes compared with the HF breed (Clark et al., 2014). Interestingly, Nieman et al. (2015) found no differences between the number visits/day between strains of HF from the United States (US) and New Zealand, although the US HF achieved more successful milkings. This is contrary to the Illawarra breed in the study of Clark et al. (2014), who although achieved more gate passes, were unable to convert these into milking events as they occurred too close to a previous milking event, resulting in no difference between the breeds for milking frequency or milk yield. Nieman et al. (2015) also identified how the pattern of milking distribution shifted between genotypes, with New Zealand HF milking at periods of overall lower visitation. This complementary use of the AM system suggests that there may be
potential to exploit behaviours among individuals or breeds in order to achieve an even distribution of milkings in the AMS. Thus, the performance of different breeds with regard to cow traffic, namely those identified previously as being suitable for CM pasture-based systems, and how these breeds complement each other with regard to milking distribution represents an area of potential investigation.

2.5.10 Social Hierarchy

Social hierarchy refers to the position assumed and dominance displayed by an animal within a herd (Syme and Syme, 1979), with these influencing an individual animal's access to resources such as feed, water (Kabuga, 1992) and, in the case of this review, the AM unit itself (Jago et al., 2003). Access to the AM unit can be impacted upon by the effect that social hierarchy has on cow traffic. Jago et al. (2003) found that cows classed as highly dominant had an 18% higher milking frequency. Similarly, as described above, Clark et al. (2014) found that the Illawara breed recorded more gate passes than the HF breed. In trying to determine the cause for the increase in gate passes Clark et al. (2014) postulated that it may have been as a result of the Illawara having a greater tendency to select out more palatable forage than HF, which would have seen them leave the paddock more quickly as the quality of pasture decreases as the sward height reduces during grazing. However, if this were the case it may also be a consequence of the Illawara breed tending to be a more dominant breed than the HF breed, as Jago et al. (2003) outlined how more dominant cows, because of their social status, were able to make their way from pasture to the AMS more quickly. Social dominance can also affect the length of time cows spend waiting in the pre-milking yard, with less dominant cows spending the longest time waiting (Ketelaar-de Lauwere et al., 1996, Jago et al., 2003, Melin et al., 2006). Interestingly, Scott et al. (2014) also
outlined how high yielding cows trafficked most quickly through the pre-milking yard; however, it is possible that this may be a result of increased udder pressure causing discomfort (Bruckmaier and Hilger, 2001), rather than a hierarchy effect. Social hierarchy has also been shown to have an influence on the distribution of milking events, with more lowly ranked cows milking between the hours of 0000 and 0600 h (Ketelaar-de Lauwere et al., 1996, Jago et al., 2003). Nieman et al. (2015) also experienced this effect, although on that occasion it was between strains of HF as opposed to identified hierarchy levels. This period of the night is widely recognised as a period of low occupancy rates of AM units (Woolford et al., 2004, John et al., 2016), suggesting that differences in dominance/hierarchy between cows induces differing behavioural responses. It is likely that lower ranked cows might choose to visit the milking unit at less popular times (such as between the hours 0000 and 0600 h), to minimise their exposure to sharing areas with dominant cows which they may fear (Lyons et al., 2014b). This may be of particular concern in a system where there is a high ratio of cow:AM unit (Rotz et al., 2003).
2.6 Conclusions and research possibilities

The intention of this review was to analyse and discuss the key factors associated with AM systems, with a particular focus on AM sustainability and cow traffic performance, which in turn affects sustainability. Key knowledge gaps have been identified from the literature which remain to be answered. Several conclusions can be drawn from this review.

Given the variation in findings between the quantitative labour studies summarised in section 2.4.1 and the reliance on once-off surveys as a data collection method, it is critical that field data is obtained in this regard. Additionally, this should be conducted through an on-going audit process to increase the accuracy of the data and to capture any variation throughout a production season; once-off surveys may be subjective, with the information provided by the farmer having the potential to be influenced by his/her current workload. Furthermore, with the exception of Jago et al. (2006b), the studies to date that have attempted to quantify the change in labour associated with AM have been conducted in confinement or partial grazing. Thus, in a pasture-based system where grass is the primary incentive for cows to traffic to the milking yard, the onus on pasture-allocation may outweigh any savings in labour from automating the milking process.

This review has also highlighted the importance of developing an understanding of total farm electricity and water consumption, encompassing an entire production season, as it provides a more accurate representation of the key consumers. This is particularly relevant to the seasonal production system, as the degree at which individual
components may consume electricity and water may coincide with milk production. Furthermore, to date both the daily and seasonal trends in electricity consumption remain undocumented. Establishing these may help develop future strategies that may increase the sustainability of the AM system.

Both labour use and electricity consumption also play an important role in the economics of an AM system. Given the popularity of AM adoption in the predominant global milk production system (confinement) and the relatively recent adoption of AM into pasture-based systems, it is not unexpected that studies examining the economic outcome of AM adoption are focused primarily on indoor production systems. Thus, the need exists to examine how AM adoption affects the economic sustainability of a dairy farm within the context of a seasonal calving pasture-based system, where calving and milk production patterns differ substantially from those found in a typical confinement system. Furthermore, taking cognisance of the increasing array of sensors and technological components available within CM parlours it is important to draw comparison not alone between AM and standard CM parlours, but also between AM and CM parlours of comparable technological standard.

While the above issues deal primarily with the sustainability of the AM system, there are substantial knowledge gaps in relation to cow traffic performance and how cows can be influenced in the context of pasture-based AM systems. Of particular importance to seasonal production systems is the effect of lactation stage on cow traffic. With the studies analysed herein indicating that late lactation cows are less motivated to traffic voluntarily for milking and more likely to experience extended milking intervals, strategies to encourage greater levels of voluntary cow traffic in late lactation should be
developed. As feed is the primary incentive for cows to traffic and taking cognisance of the potential requirement for the judicious use of concentrate supplement during the lactation period due to reduced grass growth, potential strategies should focus on examining the impact of concentrate supplementation level on cow traffic during the early and late lactation periods.

From conducting this review, it has also become clear that the findings relating to the performances of various breeds in AM systems are scant. Again this is of particular importance to AM pasture-based systems, as some breeds have been identified as being more suited to the seasonal grazing system than others. As these findings emanate from CM systems, no cognisance has been taken of the ability of these breeds to traffic voluntarily around a grazing system. Thus, this leaves a substantial void in the existing knowledge bank with regard to pasture-based AM cow traffic.

To conclude, a research duty exists to develop a greater understanding of AM within the context of a low input seasonal calving pasture-based system. If the identified knowledge gaps can be filled, it would allow farmers to make more informed decisions when considering AM adoption in such a production system and may make the technology a more attractive alternative.
Chapter 3: Daily and seasonal trends of electricity and water use on pasture-based automatic milking dairy farms

Journal of Dairy Science 101:1565 - 1578
3.1 Abstract

The objective of this study was to identify the major electricity and water consuming components of a pasture-based automatic milking (AM) system and to establish the daily and seasonal consumption trends. Electricity and water meters were installed on seven seasonal calving pasture-based AM farms across Ireland. Electricity consuming processes and equipment that were metered for consumption included milk cooling components, air compressors, AM unit(s), auxiliary water heaters, water pumps, lights, sockets, automatic manure scrapers etc. On-farm direct water consuming processes and equipment were metered and included AM unit(s), auxiliary water heaters, tubular coolers, wash-down water pumps, livestock drinking water supply, and miscellaneous water taps. Data were collected and analysed for the 12 month period of 2015. The average AM farm examined had 114 cows milking cows with 1.85 robots, performing a total of 105 milkings/AM unit per day. Total electricity consumption and costs were 62.6 Wh/L of milk produced and 0.91c/L, respectively. Milking (vacuum and milk pumping, within AM unit water heating) had the largest electrical consumption at 33%, followed by air compressing (26%), milk cooling (18%), auxiliary water heating (8%), water pumping (4%) and other electricity consuming processes (11%). Electricity costs followed a similar trend to that of consumption, with the milking process and water pumping accounting for the highest and lowest cost, respectively. The pattern of daily electricity consumption was similar across the lactation periods, with peak consumption occurring at 0100 h, 0800 h and between 1300 and 1600 h. The trends in seasonal electricity consumption followed the seasonal milk production curve. Total water consumption was 3.7 L of water per L of milk produced. Water associated with the dairy herd at the milking shed represented 42% of total farm water. Daily water
consumption trends indicated consumption to be lowest in the early morning period (0300 – 0600 h), followed by spikes in consumption between 1100 and 1400 h. Seasonal water trends followed the seasonal milk production curve, except for the month of May, when water consumption was reduced due to above average rainfall. This study provides a useful insight into the consumption of electricity and water on a pasture-based AM farm, while also facilitating the development of future strategies and technologies likely to increase the sustainability of AM systems.
3.2 Introduction

The abolition of the European Union (EU) milk quota regime has presented EU dairy farmers with the opportunity to increase milk production for the first time in over three decades. Irish milk production was predicted to have the potential to increase by 50% on pre-quota abolition levels (DAFM, 2010), with the value of that product also predicted to increase (DAFM, 2015). This increase in production is due primarily to the current under-utilization of existing animals and lands (O’Donnell et al., 2008). Additional milk production may result in a milk price reduction (Lips and Rieder, 2005) and increased milk price volatility (Dillon et al., 2016). By the end of 2016 milk production had increased by 35% over the Food Harvest 2020 baseline milk production levels (CSO, 2017); placing a substantial strain on existing dairy farm labour resources. This, in combination with the shortage of available skilled labour (Teagasc, 2017), has resulted in farmers adopting new technologies to reduce labour demand. One such technology, automatic milking (AM) systems, are being adopted to automate the milking process. This adoption is facilitated by innovative pasture management methods (Lyons et al., 2013c) which enable pasture-based farmers to maintain a large portion of grazed grass in the cows’ diet. AM systems have been found to reduce labour (Mathijs, 2004, Bijl et al., 2007, Shortall et al., 2016), and give greater time flexibility to the farm manager.

However, a significant limitation associated with the adoption of AM is the reduced profitability of the technology relative to conventional milking (CM) technologies of low to medium specification (Rotz et al., 2003, Jago et al., 2006b, Shortall et al., 2016). While the large capital cost associated with AM technology is one of the main factors
contributing this, the increased consumption of electricity associated with AM may also be considered a contributing factor (Bijl et al., 2007, Upton and O’Brien, 2013). While the consumption of electricity by both AM (Upton and O’Brien, 2013, Calcante et al., 2016) and CM systems (Upton et al., 2013) have been previously determined, the daily and seasonal trends of electricity consumption in a pasture-based AM systems remain undocumented. Furthermore, electricity consumption can be influenced by on-farm equipment, and the possibility exists to reduce electricity costs through the adoption of energy efficient and renewable technologies. However, the financial prudence of these technologies will be dependent, not alone on the capital costs of these technologies, but also on the daily trends of electricity consumption (Upton et al., 2015a).

Water is commonly used to pre-cool milk on AM farms via a tubular cooler; hence water consumption on AM farms may be significant. It is important to measure water consumption in order to gain a holistic picture of the energy water nexus on AM farms, as this is essential for comparing equipment efficiencies across farms. Furthermore, on-farm water consumption is necessary background information for the computation of a farm’s water-footprint. These data were presented by Murphy et al. (2017) for Irish CM dairy farms; however information relating to on-farm water usage on AM pasture based systems remains scant. Although Higham et al. (2017) outlined the trends in water consumption on New Zealand pasture-based CM farms, water consumption in AM systems has only been reported in relation to the milking area by Artmann and Bohlsen (2000), thus leaving the whole farm and the daily and seasonal trends undocumented. Water use also has a direct impact on electricity costs as there is an associated cost of pumping water. Thus, the objective of this study was to establish the daily and seasonal
trends of electricity and water consumption on AM dairy farms in pasture-based systems over a year long period.

3.3 Materials and Methods

This study was conducted on seven pasture-based AM farms with a spring calving system, across Ireland. These farms were selected from a database of clients associated with the extension/advisory section of the Teagasc research, training and advisory body in Ireland. To be considered for selection farms had to be pasture-based, spring-calving, milking with an AM system for at least one year and had to be willing to have electricity and water meters installed within their existing infrastructure.

3.3.1 Data collection

Data were collected for the 12 month period from January 1st to December 31st, 2015. Electricity and water consumption was recorded using a wireless monitoring system supplied by Carlo Gavazzi (Carlo Gavazzi Automation SpA, Lainate, Italy). Wireless, wide area network (WAN) routers were used to transport the data from farm to research centre, where Powersoft logging and recording software (Carlo Gavazzi Automation SpA, Lainate, Italy) calculated cumulative energy used (kWh) at 15 minute intervals for each on farm electricity and water consuming process. Dairy farm processes and equipment that were metered for electrical consumption included milk cooling components, air compressors, AM unit(s), auxiliary water heaters, water pumps, and "other", such as lights, sockets, automatic manure scrapers, etc. On-farm direct water consuming processes that were metered included AM unit(s), auxiliary water heaters,
tubular coolers, wash-down water pumps, livestock drinking water supply, and miscellaneous water taps.

The AM systems were arranged in both single unit and double unit configurations. A single unit configuration consisted of one milking crate, one robotic arm and one central compartment housing the pumping and cleaning systems. A double unit configuration consisted of two milking crates, two robotic arms and one central compartment housing the pumping and cleaning systems for both milking crates. For the purpose of the study, the term "AM unit" is the equivalent of one milking crate. Thus, when output/consumption is expressed per AM unit, it refers to the total AM system consumption divided by the number of milking crates (e.g. double configuration is divided by two). The compartmentalization of the milk pump, vacuum pump and water heater, along with individual hot and cold water supplies within the AM system did not allow for individual metering of these components, on six of the seven study farms. Thus, the electrical consumption and cost data presented in this study for milking is the combined consumption and cost of milk pumping, milking vacuum and water heating within the AM system. Water consumption data for milking is the combined consumption of both hot and cold water for cleaning of the AM plant.

Milk production data for these farms were obtained from the companies to which the milk was supplied. Cow numbers were obtained from a monthly questionnaire, completed by each farmer, in which the average numbers of lactating and non-lactating cows were recorded. Level of concentrate offered to the cows, number of milkings/unit per day and number of cows milked/unit per day were obtained from the milking system software package on six of the seven farms. These data were unavailable on farm five.
and in that instance concentrate consumption was calculated retrospectively using the farms purchase records. On-farm infrastructure with regard to the dairy shed (milk cooling, water heating etc.) were assessed on a once off visit to each farm at which time a survey of facilities was conducted.

3.3.2 Data processing

Electricity and water data from the Powersoft logging and recording software were exported to Microsoft Excel spread sheets and subsequently used to compute consumption trends for each individual farm. Electricity costs of individual farms were calculated by combining consumption data with a 2-tier pricing structure for electricity costs, based on the time of day at which the electricity consumption occurred (day tariff = 0.18 €/kWh; night tariff = 0.08 €/kWh for all consumption between 0000 and 0859h; (SEAI, 2016)). Where necessary, domestic water consumption was subtracted from total water consumption. Domestic water consumption was calculated using the number of occupants of the domestic property and the estimated usage/occupant per year, as per Irish Water guidelines (Irish Water, 2016).

The capture of the aforementioned cow inventory, milk data and AM unit performance data allowed electricity and water consumption and costs to be computed per unit of production, per cow and per milking, while also allowing the establishment of relationships between electricity consumption per milking unit and the number of milkings per unit.
3.4 Results

3.4.1 General farm characteristics

A description of the general characteristics and infrastructure on each of the seven study farms is presented in Table 3.1. Six farms milked with the same type and model of AM system. Average herd size was 114 cows, with an average annual milk production and concentrate supplementation of 5,372 litres/cow and 1,083 kg/cow, respectively. The average number of AM units was 1.85/farm with each unit performing an average of 105 milkings/day and milking an average of 49 cows, 2.15 times per day. Average production/AM unit per day across the study farms was 1,011 litres. In total, 13 AM units were monitored across the study farms, with 3 single unit configurations and 5 double unit configurations (farm 6 had two double unit configurations).
Table 3.1 Characteristics and infrastructure of the seven automatic milking (AM) study farms

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Farm</th>
<th>Farm</th>
<th>Farm</th>
<th>Farm</th>
<th>Farm</th>
<th>Farm</th>
<th>Farm</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm area (ha)</td>
<td>42</td>
<td>44</td>
<td>60</td>
<td>38</td>
<td>30</td>
<td>93</td>
<td>25</td>
<td>47</td>
</tr>
<tr>
<td>Dairy herd size (cows)</td>
<td>97</td>
<td>99</td>
<td>121</td>
<td>86</td>
<td>81</td>
<td>234</td>
<td>83</td>
<td>114</td>
</tr>
<tr>
<td>Milk production/cow per year (L)</td>
<td>7,124</td>
<td>6,068</td>
<td>6,216</td>
<td>4,768</td>
<td>5,164</td>
<td>4,130</td>
<td>4,106</td>
<td>5372</td>
</tr>
<tr>
<td>Concentrates/cow per year (kg)</td>
<td>1,684</td>
<td>1,046</td>
<td>1,284</td>
<td>1,228</td>
<td>1,111</td>
<td>543</td>
<td>690</td>
<td>1,083</td>
</tr>
<tr>
<td>Number of AM units</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>1.85</td>
</tr>
<tr>
<td>Average number of cows milked/robot per day$^1$</td>
<td>37</td>
<td>37</td>
<td>52</td>
<td>68</td>
<td>n/a$^2$</td>
<td>44</td>
<td>54</td>
<td>49</td>
</tr>
<tr>
<td>Milkings/robot per day</td>
<td>92</td>
<td>82</td>
<td>128</td>
<td>141</td>
<td>n/a$^2$</td>
<td>75</td>
<td>115</td>
<td>105</td>
</tr>
<tr>
<td><strong>Infrastructure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robot type</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>-</td>
</tr>
<tr>
<td>Vacuum pump power (kW)</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>2.2</td>
<td>1.7</td>
<td>1.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Hot wash frequency/day</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1.9</td>
</tr>
<tr>
<td>Auxiliary water heater size (L)</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>200</td>
<td>150</td>
<td>200</td>
<td>200</td>
<td>171</td>
</tr>
<tr>
<td>Air compressor number</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1.1</td>
</tr>
<tr>
<td>Air compressor power (kW)</td>
<td>3.7</td>
<td>3.7</td>
<td>3.7</td>
<td>3.7</td>
<td>2.2</td>
<td>3.7</td>
<td>3.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Milk cooling system</td>
<td>DX$^3$</td>
<td>IB$^4$</td>
<td>DX$^3$</td>
<td>IB$^4$</td>
<td>DX$^3$</td>
<td>DX$^3$</td>
<td>DX$^3$</td>
<td>-</td>
</tr>
<tr>
<td>Milk pre-cooling system</td>
<td>TC$^5$</td>
<td>TC$^5$</td>
<td>TC$^5$</td>
<td>TC$^5$</td>
<td>TC$^5$</td>
<td>TC$^5$</td>
<td>TC$^5$</td>
<td>-</td>
</tr>
<tr>
<td>Wash pump power (kW)</td>
<td>1.1</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.7</td>
<td>1.5</td>
<td>1.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>

$^1$Average for each day that each robot was in use and excludes non-lactating cows

$^2$n/a = Not available

$^3$DX = Direct expansion cooling system

$^4$IB = Ice bank cooling system

$^5$TC = Tube cooler
3.4.2 *Electricity consumption and costs analysis*

The electricity consumption and costs for each of the electricity consuming processes and their contribution to the total farm electricity consumption and cost are outlined in Table 3.2. Total electricity consumption was 62.6 Wh of electricity per litre of milk produced (range 47 - 84 Wh/L) or 336 kWh/cow (range 246 - 422 kWh/cow). In total, 53% of all electricity consumed by the study farms occurred during the period of the higher cost day rate tariff. The average cost of electricity on the study farms was 0.91c/L (range 0.67 - 1.22c/L) or 49 €/cow (range 36 - 57 €/cow) over the 12-month period. Electricity used in the dairy milking shed accounted for 85% of the total electricity consumed on-farm. Within the dairy milking shed, the major processes of electricity consumption were milking (33%), air compressing (26%), milk cooling (18%), auxiliary water heating (8%); water pumping (4%) and other (11%) comprised the remaining proportions, with these consumptions occurring both within and external to the milking shed.
Table 3.2 Breakdown of the consumption and cost of electricity per litre of milk sold and per cow on the seven study farms for a 12 month period

<table>
<thead>
<tr>
<th>Consumption</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>c/L&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Wh/L kWh/cow % total consumption</td>
<td>% day rate tariff usage&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Milking&lt;sup&gt;3&lt;/sup&gt;</td>
<td>20.7 111</td>
</tr>
<tr>
<td>Air compressor</td>
<td>16.5 87</td>
</tr>
<tr>
<td>Milk cooling</td>
<td>11.3 60</td>
</tr>
<tr>
<td>Auxiliary water heating</td>
<td>4.4 27</td>
</tr>
<tr>
<td>Water pumping</td>
<td>2.7 13</td>
</tr>
<tr>
<td>Other&lt;sup&gt;4&lt;/sup&gt;</td>
<td>7 37</td>
</tr>
<tr>
<td>Total</td>
<td>62.6 336</td>
</tr>
</tbody>
</table>

<sup>1</sup>Percentage of electricity consumed from 0900 to 2359 h  
<sup>2</sup>c/L = cents per litre of milk sold  
<sup>3</sup>Milking = All use by the milking robot(s) including vacuum pump and water heating within robot(s)  
<sup>4</sup>Other = Components such as lighting and motorized manure scrapers  
<sup>5</sup>Average percentage day rate tariff usage
**Milking.** Milking encompasses the processes of milk pumping, vacuum pumping, water heating within the AM system and miscellaneous electrical devices associated with the AM system. For the average AM farm described in this study, milking was the largest electricity consuming process (33%) at 20.7 Wh/L (range 14 - 26 Wh/L) and a cost of 0.30c/L (range 0.21 - 0.35c/L). Fifty-nine percent (range 44 - 67%) of this consumption occurred during the day rate tariff.

Electricity consumption and cost/AM unit for the average unit and for each configuration (single and double units) are outlined in Table 3.3. The average AM unit consumed 7,361 kWh during 2015, with the average single unit consuming approximately 55% more electricity per unit at 9,186 kWh than the average unit from a double configuration (5,992 kWh). A similar trend existed when the systems were analysed by day. However, consumption per milking was similar between the single and double unit systems at 0.20 and 0.19 kWh per milking, respectively. The average electricity cost of operating an AM unit was €991 per year, with the trend in electricity costs between configurations (single and double) and metrics (per milking day and per milking) mirroring that of electricity consumption.

The relationship between the average electricity consumption/AM unit per day and the average number of milkings/day is outlined in Figure 3.1a. An $R^2$ of 0.44 existed between daily electricity consumption/AM unit (kWh) and the number of milkings/AM unit per day, with consumption/day increasing as milkings/day increased. The relationship between the number of milkings/AM unit per day and electricity consumption/day when expressed per unit of milk produced (Wh/L), had an $R^2$ of 0.46, with consumption per day deceasing as the number of milkings increased.
Table 3.3 The average electricity consumption and cost per individual automatic milking (AM) unit, for the average AM unit, a single unit configuration and double unit configuration. Data is presented on an annual, per milking day and per milking event (ranges in parenthesis)

<table>
<thead>
<tr>
<th></th>
<th>Consumption (kWh)</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average unit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>7,361 (5,247–9,503)</td>
<td>991 (767–1,339)</td>
</tr>
<tr>
<td>Per milking day¹</td>
<td>20.5 (15.0–26.0)</td>
<td>2.76 (2.10–3.67)</td>
</tr>
<tr>
<td>Per milking</td>
<td>0.19 (0.12–0.23)</td>
<td>0.027 (0.018–0.032)</td>
</tr>
<tr>
<td><strong>Single unit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>9,186 (8,650–9,503)</td>
<td>1,179 (1,002–1,339)</td>
</tr>
<tr>
<td>Per milking day¹</td>
<td>25.2 (23.7–26.0)</td>
<td>3.23 (2.75–3.67)</td>
</tr>
<tr>
<td>Per milking</td>
<td>0.20 (0.18–0.21)</td>
<td>0.027 (0.026–0.028)</td>
</tr>
<tr>
<td><strong>Double unit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>5,992 (5,247–6,770)</td>
<td>850 (767–995)</td>
</tr>
<tr>
<td>Per milking day¹</td>
<td>17.0 (15.0–19.0)</td>
<td>2.41 (2.10–2.62)</td>
</tr>
<tr>
<td>Per milking</td>
<td>0.19 (0.12–0.23)</td>
<td>0.027 (0.018–0.032)</td>
</tr>
</tbody>
</table>

¹Consumption and cost for each day the system was milking

**Air Compressor.** The requirement for compressed air accounted for 26% of all electricity consumed on the study farms, requiring 16.5 Wh/L (range 13–23 Wh/L) and costing 0.24c/L (range 0.19–0.35c/L). Sixty-five percent (range 63–69%) of this consumption occurred during the higher day rate tariff. The relationship between the average electricity consumption/air compressor per day and the average number of milkings/day is outlined in Figure 3.1b. An R² of 0.56 existed between daily electricity consumption/AM unit (kWh) and the number of milkings/air compressor per day, with consumption/day increasing as milkings/day increased. The relationship between the number of milkings expressed/air compressor per day and electricity consumption/day when expressed per unit of milk production (Wh/L) had an R² of 0.23, with consumption/day tending to decrease as the number of milkings/day increases.
Figure 3.1 The relationship between (a) the number of milkings/AM unit per day and daily electricity consumption per AM unit and (b) the number of milkings/air compressor per day and daily electricity consumption per air compressor. Daily electricity consumption is expressed as kilowatt-hours and watt-hours per litre of milk produced. Each data point represents the average number of milkings/day and the average consumption/day for each of the 12 months in the study period for six of the study farms.
**Milk Cooling.** Milk cooling was the third largest electrical consuming process at 18% of total consumption. This resulted in 11.3Wh of electricity being consumed for every litre of milk produced (range 6.4 - 21.6 Wh/L), with 59% (range 34 - 75%) of this being consumed during the day tariff period. Similar to the trend for electrical consumption, milk cooling was the third largest electricity cost at 0.17c/L (range 0.09 - 0.25c/L). Average milk cooling efficiency (litres of milk cooled by 1 kWh) on the study farms was 88 L/kWh (range 46 - 156 L/kWh).

**Auxiliary Water Heating, Water Pumping, Other.** These represented the smallest electrical consuming processes and costs on the study farms at 4.4 Wh/L and 0.07c/L, 2.7 Wh/L and 0.03c/L, and 7 Wh/L and 0.10c/L, respectively. Auxiliary water heating included heating of water for cleaning of the milk storage tank; water pumping included both supply and wash pumps; while “other” included lights, sockets and automatic manure scrapers.

### 3.4.3 Electricity consumption trend analysis

**Seasonal Trends.** The seasonal effect of electricity consumption is outlined in Figure 3.2. The profile of consumption followed a similar profile to the milk production curve of a seasonal production system. This was due to the fact that 85% of total farm electricity consumption occurred in the milking shed. Total monthly farm consumption was at its lowest in January at 1,798 kWh, before rising steadily to 3,538 kWh in March. From there, consumption remained consistent between March and July, peaking slightly in May at 3,579 kWh. From July consumption reduced gradually before reaching its second lowest point of the year at 2,493 kWh in December. When the trend was analysed in Wh/L, it was the inverse of the milk production curve, with
consumption at its lowest in June at 47 Wh/L, while peaking in January, February and December at 161, 121 and 120 Wh/L, respectively.

![Figure 3.2 Seasonal trend in total electricity consumption for the average of seven pasture-based automatic milking study farms over a 12 month period, expressed in kilowatt-hours (kWh) and watt-hours/litre of milk produced (Wh/L)](image)

**Daily Trends.** The daily profile of electricity consumption on-farm is shown in Figures 3.3 a, b and c for March 24 and 25, May 25 and 26 and September 15 and 16, 2015, respectively. These days were chosen as representative days during the early, peak and late lactation periods to illustrate the nature of the electricity consumption profile. While the peaks and troughs of consumption were more pronounced in the late lactation period, the pattern of consumption was similar across the lactation periods, with peaks at 0100 h, 0800 h and between 1300 and 1600 h.
Figure 3.3 Average percentage of daily total electricity consumption on-farm in (a) early lactation (March 24 to 25, 2015) (b) peak lactation (May 25 to 26, 2015) and (c) late lactation (September 15 to 16, 2015) for seven pasture-based commercial automatic milking farms
3.4.4 Water consumption analysis

The water consumption for each of the main water consuming processes is outlined in Table 3.4. In total, 3.7 L of on-farm direct water was required to produce one litre of milk across the seven pasture-based AM study farms monitored. This equates to 2,286,999 litres per year or 55 L/cow per day. Water consumption was split between water required for livestock/miscellaneous and the dairy shed at 58% and 42%, respectively. Water consumed by livestock/miscellaneous purposes was 2.2 L/L of milk, which equated to 32 L/cow per day.

Milking Process. The milking process encompassed the use of water for cleaning the AM unit (both cold and hot water), pre-cooling of milk, auxiliary hot water and washing down of the milking shed. Total direct water consumption for the milking process was 957,693 litres/ year (2,623 L/day) or 1.5 L/L of milk. Pre-cooling of milk in the tube-cooler had the largest requirement for water, followed by milking (AM units), the wash-down process and auxiliary water heating. The average AM unit consumed 159,399 L/year or 445 L/milking day (Table 3.5). Single unit configurations consumed 34,880 litres more water/unit over the 12 month period (82 L/day) than double unit configurations. However, when analysed per milking event (i.e. one cow milking), the single unit configurations consumed 3.9 L/unit per milking, while the double unit configurations consumed 4.5 L/unit per milking.
Table 3.4 Total direct water use on the seven study farms for a 12 month period

<table>
<thead>
<tr>
<th></th>
<th>Litres</th>
<th>SD</th>
<th>L/L¹</th>
<th>SD</th>
<th>L/cow per day²</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total supply</td>
<td>2,286,999</td>
<td>650,455.7</td>
<td>3.7</td>
<td>0.53</td>
<td>55.0</td>
<td>4.80</td>
</tr>
<tr>
<td>Livestock and miscellaneous³</td>
<td>1,329,306</td>
<td>351,113.2</td>
<td>2.2</td>
<td>0.67</td>
<td>32.0</td>
<td>13.26</td>
</tr>
<tr>
<td>Milking process⁴</td>
<td>957,693</td>
<td>429,483.9</td>
<td>1.5</td>
<td>0.92</td>
<td>23.0</td>
<td>9.55</td>
</tr>
<tr>
<td>Milking⁵</td>
<td>317,568</td>
<td>175,137.7</td>
<td>0.5</td>
<td>0.11</td>
<td>7.6</td>
<td>0.68</td>
</tr>
<tr>
<td>Milk pre-cooling</td>
<td>729,652</td>
<td>404,594.2</td>
<td>1.2</td>
<td>0.74</td>
<td>17.5</td>
<td>10.24</td>
</tr>
<tr>
<td>Auxiliary water heating</td>
<td>27,953</td>
<td>6,319.3</td>
<td>0.1</td>
<td>0.03</td>
<td>0.7</td>
<td>0.27</td>
</tr>
<tr>
<td>Wash-down⁶,⁷</td>
<td>208,244</td>
<td>160,630.0</td>
<td>0.3</td>
<td>0.15</td>
<td>5.0</td>
<td>1.58</td>
</tr>
</tbody>
</table>

¹L/L = Litres of water consumed/litre of milk sold  
²L/cow = Litres of water/dairy cow per day  
³Water consumed by livestock and other miscellaneous use  
⁴Sum of milking process components does not equal milking process total, due to the recycling of water within the milking process network  
⁵Water consumed by the milking robot(s)  
⁶Water consumed through the washing of the milking area  
⁷Includes recycled water
Table 3.5 The average water consumption per individual automatic milking (AM) unit for the average AM unit, a single unit configuration and a double unit configuration. Data is presented on an annual, per milking day and per milking event (ranges in parenthesis)

<table>
<thead>
<tr>
<th>Consumption (Litres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average unit</td>
</tr>
<tr>
<td>Annual</td>
</tr>
<tr>
<td>Per milking day¹</td>
</tr>
<tr>
<td>Per milking</td>
</tr>
<tr>
<td>Single unit</td>
</tr>
<tr>
<td>Annual</td>
</tr>
<tr>
<td>Per milking day¹</td>
</tr>
<tr>
<td>Per milking</td>
</tr>
<tr>
<td>Double unit</td>
</tr>
<tr>
<td>Annual</td>
</tr>
<tr>
<td>Per milking day¹</td>
</tr>
<tr>
<td>Per milking</td>
</tr>
</tbody>
</table>

¹Consumption for each day the system was milking

Water Recycling. Water that was used in the tube-cooler for pre-cooling milk was recycled to the wash-down process, the AM units and livestock/miscellaneous purposes (Table 3.6). Of the water made available for recycling, livestock/miscellaneous process availed of the greatest proportion of it (55%), followed by the wash-down process (29%) and the AM units (16%). However, when analysing the recycled water as a proportion of the total consumption for each of the three components, it comprised 100% of the water used for the wash-down process, 37% of the water for the AM units and 23% of the water for livestock/miscellaneous.

Table 3.6 The proportion of tube-cooler recycled to water consuming process and the proportion of total water for each of those processes obtained from the tube-cooler

<table>
<thead>
<tr>
<th>% of tube-cooler water</th>
<th>% of total component water obtained from tube-cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wash-down process</td>
<td>29</td>
</tr>
<tr>
<td>Livestock and miscellaneous</td>
<td>55</td>
</tr>
<tr>
<td>Milking (AM units)</td>
<td>16</td>
</tr>
</tbody>
</table>
3.4.5 *Water consumption trend analysis*

**Seasonal Trends.** The seasonal trend of water consumption is outlined in Figure 3.4. Similar to the seasonal electricity consumption profile, water consumption followed a comparable trend to the milk production curve of a seasonal production system. Consumption was at its lowest in January and December at 105,464 and 126,166 litres, respectively. Consumption peaked at 264,051 litres in June. However, contrary to the milk production curve, consumption in May was reduced compared with the preceding and the succeeding two months. When the trend was analysed on L/L basis, it was again the inverse of the milk production curve, with consumption at its lowest in May at 2.6 L/L, while peaking in January, February and December at 6.9, 6.2, and 6.1 L/L, respectively.

![Figure 3.4 Seasonal trend in total farm direct water consumption for the average of seven automatic milking study farms over a 12 month period, expressed in litres and litres of water/litre of milk produced (L/L). Seasonal livestock/miscellaneous water consumption is also outlined in litres](image-url)
Daily Trends. The daily profile of water consumption is illustrated in Figures 3.5 a, b and c for March 24 and 25, May 25 and 26 and September 15 and 16, 2015, respectively. These days were chosen as representative days during the early, peak and late lactation periods to illustrate the nature of the water consumption profile. Water use followed a similar pattern across all three lactation time points. Irrespective of season, water use was at its lowest in the early morning period (0300 – 0600 h; 0.8 – 1.4% of total daily consumption), with spikes in consumption from 1100 to 1400 h (6.5 – 9.6% of total daily consumption).
Figure 3.5 Average percentage of daily total direct water consumption on-farm in (a) early lactation (March 24 to 25, 2015) (b) peak lactation (May 25 to 26, 2015) and (c) late lactation (September 15 to 16, 2015) for seven pasture-based commercial automatic milking farms
3.5 Discussion

3.5.1 Electricity

The total farm electricity consumption and costs of the AM farms in this study were greater than those outlined by Upton et al. (2013) on an average Irish CM pasture-based system. This occurred despite the fact that the proportion of electricity used during the higher cost day rate period (0900 - 2359 h) was 10% less in the current study compared with that of Upton et al. (2013). Interestingly, Upton et al. (2015b) outlined that the day and night rate tariff was the most suitable electricity pricing structure for dairy farms. Bijl et al. (2007) and Steeneveld et al. (2012) both outlined greater electricity costs for AM systems compared with CM systems on Dutch dairy farms. The main contributors to the consumption of electricity in the current study were milking, air compression and milk cooling; together accounting for 77% of total consumption.

The largest of these processes was milking, which included the vacuum pump, milk pump and water heating within the AM system. Calcante et al. (2016) described how the average AM unit, while configured to perform three hot wash cycles per day, used 1.2 kWh/100 L of milk. This is less than the 2.1 kWh/100 L of milk reported in the current study. However, the current study was reflective of a full lactation of a seasonal production system, encompassing the shoulder periods of the lactation when small numbers of cows were milking. The farms in this study had an average of 105 milkings/day per AM unit, while Calcante et al. (2016) achieved an average of 156 milkings/day per AM unit. Hence, there is an inherent base-line electricity demand generated by a fixed number of hot wash cycles per day, irrespective of the number of milkings per day. This is further illustrated in Figure 3.1a which revealed that as the
number of milkings/AM unit increased, the electricity consumption per litre of milk decreased.

The single unit configurations monitored in the current study used more electricity (gross kWh)/AM unit on an annual and daily basis than the double unit configurations. However, both configurations used a similar quantity of electricity per milking. This would indicate that the differences in electricity consumption per AM unit are as a result of differing stocking densities/AM unit, with single unit configurations tending to have a higher ratio of cows/unit than double unit configurations (84 v 54 cows/AM unit), resulting in a higher number of milkings/AM unit per day. This may also be observed in Figure 1a where electricity consumption/day (kWh) increased as milkings per day increased ($R^2 = 0.44$). Thus, 44% of the variation in electricity consumption/AM unit can be accounted for by the number of milkings performed. Interestingly, one of the AM types monitored in this study allowed for the individual metering of the vacuum pump and AM water heater. This showed that water heating for the AM system accounted for 61% of the unit consumption, with the vacuum pump accounting for 27% and robot (including milk pump) using 12%. This breakdown facilitates comparisons with the AM system analysed by Upton and O’Brien (2013); a study which highlighted the frequency of hot washing of the milking equipment as a major difference between an AM and a CM system, and is contrary to the findings of Artmann and Bohlsen (2000) who found the vacuum pump to be the main electricity user. The average AM farm, in the current study, hot washed the milking unit(s) 1.85 times/day, whereas a typical CM farm may only hot wash on alternate days to coincide with the washing of the milk storage tank upon milk collection (Upton et al., 2015a).
The requirement for compressed air for the cleaning of milk lines and the opening and closing of entry and exits gates represented a main difference in electricity consumption between AM and CM systems (Upton and O'Brien, 2013). This component alone accounted for >25% of the total farm electricity consumption in the current study. A study by Calcante et al. (2016) established that a wrongly sized air compressor can increase electricity consumption by 25 kWh/day, resulting in substantially increased running costs. Similar to the AM unit, there was a tendency for the consumption of electricity associated with the air compressor to increase as milkings increased. This is expected given that the air compressor is heavily involved in the guidance of the robotic arm, operating the entry and exits gates on the AM unit, drafting gates and post-selection grazing gates. Milk cooling was the third largest consumer of electricity on the farms measured, at 11.3 Wh/L. This resulted in a milk cooling efficiency of 88 L/kWh. This was 11 L/kWh more efficient than the CM cooling systems described by Upton et al. (2013) and is likely a consequence of a more gradual and constant supply of milk through the tubular cooler and into the milk storage tank, since an AM unit is operational for milking for almost 24 hours/day.

The seasonal electricity consumption trend followed a similar pattern to the seasonal spring calving milk production curve. This is due to the fact 85% of total electricity consumption occurred in the milking shed. There was a greater volume of milk to cool in the mid-lactation period as cows are producing peak milk volumes at that time. This period of maximum milk production also necessitates a greater number of milkings/AM unit per day and as demonstrated earlier, electricity consumption/AM unit increased as the number of milkings increased. However, when the trend was analysed per litre of
milk production a dilution effect can clearly be seen, with the months of greatest milk production resulting in the lowest consumption per litre.

Daily electricity consumption profiles follow a substantially different trend to that of the CM system described by Upton et al. (2013), which followed the pattern of twice daily batch milking. The trend in the current study, irrespective of season, was more consistent, represented by multiple smaller peaks in consumption each day, with maximum consumption/hour at the highest point being 6.5% of daily total. This results in a more constant demand for electricity, which in turn may make AM systems more suitable than CM systems for operation in association with renewable energy technologies. Electricity consumption was at one of its lowest points in the early morning period. Although milking distribution data was not measured in the current study, this time coincided with a recognized period of reduced visitation and low robot utilization (John et al., 2016). Variation between seasons was limited with the late lactation period displaying more pronounced peaks and troughs compared to early lactation. Again, this may be a direct result of a lower utilization rate of the AM unit during the troughs in late lactation.

3.5.2 Water

Total on-farm direct water consumption was 3.7 litres of water/litre of milk sold. This is less than the 11.7 L/L, 6.4 L/L and 5.7 L/kg FPCM outlined for CM pasture-based systems by Ridoutt et al. (2010), Murphy et al. (2014) and Murphy et al. (2017), respectively. The average of 55 L/cow per day reported in this study, was also substantially less than the 113 L/cow per day reported by Higham et al. (2017) for New Zealand non-irrigated CM pasture-based systems, although 26% of livestock drinking
water was reported to be lost to leaks on the New Zealand farms. Water use was split
42:58 percent between the milking process and livestock/miscellaneous, respectively.
Thus, water consumption associated with the milking process was 1.5 L/L. Pre-cooling
of milk represented the largest consumer of water within the milking process and was in
agreement with Murphy et al. (2014) in relation to CM systems. However, the
consumption was 0.5 L/L less in the average AM pre-cooling system of the current
study compared with the CM system of Murphy et al. (2014). An average milk cooling
ratio of 1.2 litres of water for each litre of milk (range 0.7 to 2.1 L/L) was observed at
the tubular cooler. Finding efficient recycling strategies for this pre-cooling water will
be key for reducing the direct water-footprint of the dairy farm (Murphy et al., 2014). In
the current study, this water was used on-farm by the milking robots and for the wash­
down of the milking area, with the milking robot(s) consuming 0.5 L/L, with 37% of
this water coming from a recycled source (e.g. water from the pre-cooling process).
However, the water requirement for washing down the milking area in the current study
was less than that for washing down CM parlours as outlined by Murphy et al. (2014).
This may be a consequence of the AM unit requiring a smaller housing area and cow
collecting yard, resulting in a reduced area of solid concrete flooring requiring washing,
compared with CM parlours. Therefore, there was an opportunity to find other suitable
uses for this recycled tubular cooler water on AM farms.

The average AM unit in this study used 159,399 litres of water per annum. This equates
to 4.3 litres per milking, similar to the average of 4.7 litres outlined by Jensen (2009),
for AM units of similar make and type to those examined here, although they operated
in contrasting production systems. The average single unit AM configuration used 24%
more water on an annual basis than the average double unit configuration, but
consumed 12.5% less per milking event over the 12 month period measured. This is likely to be a consequence of the different stocking densities on the AM units, resulting in the dilution of water used within the AM unit across a greater number of milkings.

On-farm well water used by livestock/miscellaneous purposes was 32 L/cow per day, slightly less than the 35 L/cow per day outlined by Higham et al. (2017). However, as there was surplus water from the tubular cooler due to the small portion recycled for washing, AM farms were able to store this water and use for it for livestock drinking consumption/miscellaneous purposes. This led to a further 403,288 litres of recycled water being consumed by livestock/miscellaneous process, replacing on-farm well water. Thus, total livestock/miscellaneous consumption was 42 L/cow per day with 23% of this provided from a recycled source. Morris et al. (2010) and Jago et al. (2005) outlined that lactating dairy cows consumed 41 and 54 L/cow per day, respectively at varying lactation stages, while Higham et al. (2017) found that before accounting for any potential leaks in the drinking water network, average consumption across a 12 month period may be as high as 60 L/cow per day.

Seasonal water use followed a similar pattern to the milk production curve of a spring calving system, with lowest demand for water in the winter months and highest demand in the summer months. This is expected as spring calving herds have the majority of cows milking in the summer months, resulting in a greater number of milkings in each day. With this comes greater water consumption in the form of additional between milking cluster cleaning and tubular cooler consumption. Additionally, drinking water consumed by livestock is greatest in the summer months (Higham et al., 2017). However, the seasonal water trend deviated from the milk production curve in May, with this month recording above average rainfall (60 vs 106 mm; Met Eireann, 2015),
resulting in livestock drinking less. Morris et al. (2010) demonstrated that a daily rainfall level of 26mm can reduce livestock drinking water consumption by as much as 62%. Again, when the trend of water consumption was analysed per litre of milk, a dilution effect (or lack thereof) can clearly be observed, with the months with the lowest milk production and water use recording the greatest consumption per litre of milk. Similar to electricity consumption, water consumption was at its lowest in the early morning period (0400 – 0600 h) when AM unit utilization is traditionally at its lowest (John et al., 2016). Since > 70% of water consumption occurring between 0900 and 2359 h, it is not surprising that water pumping recorded the highest proportion of electricity usage during the more expensive day tariff period.

3.5.3 Additional considerations

Achieving a large and consistent number of milkings throughout the year is not realistic in a seasonal calving system as the majority of the herd reaches maximum milk production at the same time. While the average number of milkings/AM unit per day was 105 across the year on the farms analysed in the current study, the average number of milkings/AM unit per day at peak milk production was 128 (range 99 – 159) from an average of 58 cows (range 45 – 82). These figures were lower than the potential maximum number of milkings/AM unit per day of 180 from 77 cows, for a seasonal calving system, as outlined by Lyons and Kerrisk (2017). As observed in the current study, increasing the number of milkings/AM unit had an impact on reducing the electricity consumption per litre of milk. Replicating the potential performance at peak milk production as outlined Lyons and Kerrisk (2017) would have a positive impact, but would require an efficient milking strategy.
Ferneborg and Svennersten-Sjaunja (2015) and Ferneborg et al. (2016) have described potential pulsation settings and cluster removal strategies, respectively, to increase the throughput of cows through the AM unit, thus increasing the number of milkings per day. While electricity usage associated with milk cooling, vacuum and milk pumps and compressed air would increase in accordance with increased milkings/AM unit, water heating costs would reduce as hot washing of the AM unit is performed at a fixed frequency each day, irrespective of number of milkings. A similar scenario applies to water consumption, with a fixed quantity of water required per wash cycle. Therefore, an increased number of milkings would result in a dilution of the costs associated with (hot) washing of the AM unit. However, it should also be taken into consideration that increasing the milkings/AM unit may accelerate the maintenance and replacement of machine parts (Lyons and Kerrisk, 2017).

3.6 Conclusion

This study provides an understanding of the factors contributing to the daily and seasonal trends of electricity and water use on pasture-based AM farms. Milking and compressed air were the largest and most expensive consumers of electricity. Although farms with single unit configurations consumed more electricity (total kWh per annum) than double unit configurations, there was no difference in consumption per milking, indicating that increased consumption was caused by a greater ratio of cows per AM unit on single unit farms. Trends indicate that while electricity consumption by the AM unit and air compressor increased with increased milkings, consumption per litre of milk produced was reduced. Water for livestock/ miscellaneous purposes and for pre-cooling milk were the largest consumers of on-farm direct water. Both seasonal and
daily trends in consumption were similar for electricity and water consumption, with seasonal trends following the milk production curve of a seasonal production system. These findings have the potential to assist in developing future strategies that may improve the competitiveness of the AM system.
Chapter 4: Investment appraisal of automatic milking and conventional milking technologies in a pasture-based dairy system

Journal of Dairy Science 99:7700 - 7713
4.1 Abstract

The successful integration of automatic milking (AM) systems and grazing has resulted in AM becoming a feasible alternative to conventional milking (CM) in pasture-based systems. The objective of this study was to identify the profitability of AM in a pasture-based system, relative to CM herringbone parlours with two different levels of automation, across two farm sizes, over a 10-year period following initial investment. The scenarios which were evaluated were (i) a medium farm (MF) milking 70 cows twice daily, with one AM unit, a 12 unit CM medium specification (MS) parlour and a 12 unit CM high specification (HS) parlour, and (ii) a large farm (LF) milking 140 cows twice daily with two AM units, a 20 unit CM MS parlour and a 20 unit CM HS parlour. A stochastic whole-farm budgetary simulation model combined capital investment costs and annual labour and maintenance costs for each investment scenario, with each scenario evaluated using multiple financial metrics, such as annual net profit, annual net cash flow, total discounted net profitability, total discounted net cash flow and return on investment. The capital required for each investment was financed from borrowings at an interest rate of 5% and repaid over 10-years, while milking equipment and building infrastructure were depreciated over 10 and 20-years, respectively. A supporting labour audit (conducted on both AM and CM farms) showed that there was a 36% reduction in labour demand associated with AM. However, despite this reduction in labour, MS CM technologies consistently achieved the greater profitability, irrespective of farm size. AMS achieved intermediate profitability at MF size while, it was 0.5% less profitable than HS technology at the LF size. The difference in profitability was greatest in the years after the initial investment. This study indicated that while milking with AM was less profitable than MS technologies, it was competitive when compared with a CM parlour of similar technology.
4.2 Introduction

The first automatic milking (AM) system was commercialized in the Netherlands in 1992 and the concept has since become common around the world, with more than 10,000 farms using the technology (de Koning, 2011). It is envisaged in the future that up to 50% of new milking parlour installations in many European Union (EU) countries will be AM (O’Brien et al., 2015b). However, the vast majority of these are integrated with indoor cow management systems. The combination of AM and grazing was first reported in the early 2000’s in Australia and New Zealand by Greenall et al. (2004) and Jago et al. (2004). The successful integration of AM and grazing has resulted in AM systems becoming a feasible alternative to conventional milking (CM) in pasture-based systems worldwide. Given the comparative advantage that grass-based systems have in reducing total costs of production (Dillon et al., 2005), and the increased sustainability associated with grass-based systems (O’Brien et al., 2012b), it is essential that the adoption of AM does not lead to a reduction of the proportion of grazed grass in the cows diet, as shown by Van Dooren et al. (2004). This is also important from an international perspective as Van den Pol van Dasselaar et al. (2010) demonstrated that in the Netherlands, the greater the proportion of grazed grass consumed by the cow, the larger the income profit compared to non-grazing farms, while Hanson et al. (1998) and Hofstetter et al. (2014) showed that grazing systems had a higher return than confinement systems in the United States and Switzerland, respectively.

Milk produced from grass can now command a premium price with the largest milk processor in the Netherlands, Friesland Campina, offering milk producers a price incentive to increase the time cows spend at grass (Reijs et al., 2013). This can create
potential opportunities for new markets for dairy produce, as the green image associated with cows grazing pasture continues to appeal to consumers, due to the improved milk quality (Lock and Garnsworthy, 2003) and animal health (Thomsen et al., 2007). Innovative methods of pasture management, have increased the compatibility of AM with grazing (Lyons et al. (2013c), while Nieman et al. (2015) has investigated the optimal animal genotype and supplementation type for a pasture-based AM system in the United States. While these studies have shown that AM can be integrated into grazing systems, an economic evaluation specific to pasture-based systems is required to allow farmers to objectively assess if an investment in AM would be prudent given the specific costs and economic returns of producing milk from grazed grass. Irrespective of region or production system economics are a vital pillar of sustainability and should be focused on regardless of intensity of AM systems within a country. This is particularly relevant in an Irish context at the present time, as given the rapid increase in popularity of the AM system and the abolition of the EU milk quota regime, many farmers are faced with a decision regarding investment in milking technology.

The two main reasons cited for investing in AM are social and economic (Bijl et al., 2007). The most prevalent social reason is undoubtedly the association of AM with the reduced labour demand on farms and in particular greater time flexibility (Hogeveen et al., 2004) due to reduced unsocial labour requirements. The milking task in a conventional parlour is a labour intensive process which takes place from once to thrice but mostly twice daily for up to 300 days of the year (Jago and Woolford, 2002). This accounts for up to 33% of total dairy labour input on pastured based dairy farms (O'Donovan et al., 2008). Additional to this, it is a task which rarely occurs during normal business hours, which can make it a challenging task to attract and retain skilled
labour for (Tarrant and Armstrong, 2012). While studies may disagree with regard to the magnitude of the reduction in labour associated with AM (Sonck, 1995, Mathijs, 2004, Bijl et al., 2007), all of the studies are in agreement that AM reduces labour demand as it eliminates physical tasks associated with milking, such as milking cluster attachment and detachment, and some herding of cows for milking. The labour associated with AM systems includes visual monitoring of milking and cow data, cleaning and checking of attention lists on AM systems (Steeneveld et al., 2012). Consequently, farmers with AM systems report improved physical and mental health and improved lifestyles (Mathijs, 2004) associated with the investment in AM. Furthermore, AM allows operators some time flexibility as their presence is no longer required at specific milking times; this can create potential for alternative engagement, which might include off-farm employment. This reduction in physical labour demand and the increase in time flexibility represent an improved social aspect to dairy farming and these also were the main reasons cited by Dutch dairy farmers for the adoption of AM (Hogeveen et al., 2004).

However, AM is regarded as a system that requires two to three times more capital, initially, than the CM herringbone parlour (Rotz et al., 2003). Higher capital costs, combined with higher running costs, has prompted the majority of studies examining the economics of AM to suggest, that AM was not cost effective when examined solely on a financial return basis (Dijkhuizen et al., 1997, Rotz et al., 2003, Jago et al., 2006b). Moyes et al. (2014) established that concerns for farmers in the United States included cash flow and profitability, when transitioning to AM systems. However, many such studies examined the economics of AM relative to conventional parlours that had little automation. It is crucially important to establish the economic parameters of AM.
relative to CM herringbone parlours, with different levels of automation and technology.

In order to obtain finance for modernization and mechanization in the future, dairy farmers will be required to develop robust financial plans to allow investment to provide optimal labour efficiency and financial return. Many complex factors must be considered and simulation models have been developed to identify optimum investment strategies. These are necessary to understand the relationship between capital costs, financing structures, labour productivity, inflation, farm inputs and outputs, and price volatility (Rotz et al., 2003, Shalloo et al., 2004, Jago et al., 2006b). Such models have the ability to assess the financial return to the farm over an extended period, based on the rate of capital investment and allocation of resources.

The objective of this study was to identify the profitability of AM relative to CM herringbone parlours with two different levels of technology, over a 10-year period across two farm sizes, in a pasture-based system using a number of different financial metrics.

4.3 Materials and Methods

In order to examine the economic parameters associated with investing in AM technology compared to two CM parlours with different technology levels (medium and high), and suitable for two different herd sizes (70 and 140 cows), a number of different components of the systems were measured and defined. These included; initial machine and infrastructural investment costs; annual machine maintenance; energy use; machine
running costs and on-farm dairy labour input, all of which were incorporated into the Moorepark Dairy Systems Model (MDSM; Shalloo et al. (2004); see model description below). Three different parlour types were assessed; (i) an AM system, (ii) CM system of medium specification (MS) and (iii) CM system of high specification (HS) (see scenario description below). These systems were evaluated as relevant to two different farm sizes; a medium sized farm (MF) milking 70 cows and large sized farm (LF) milking 140 cows.

4.3.1 Scenario description

All six milking technology investment scenarios were simulated based on the assumption that the respective farm operated a spring-calving pasture-based dairy system and where existing milking facilities on the farm were outdated – thus requiring a completely new milking infrastructure on a green-field site. The six investment scenarios may be described as follows:

Automatic Milking System (AMS) Single Unit (AMS-SU). One AMS unit milking 70 cows twice daily.

12 Unit MS CM Parlour (12MS). 12 unit herringbone milking parlour, milking 70 cows twice daily with MS technology (batch feeders in the milking parlour and swing-over arms).

12 Unit HS CM Parlour (12HS). 12 unit herringbone milking parlour milking 70 cows twice daily with HS technologies (individual electronic cow feeders, swing-over arms, automatic cluster removers, electronic milk meters, automatic identification, automatic
drafting, automatic washer, automatic cluster cleaning between individual cow milkings and an electronic milk diversion line).

**AMS Double Unit (AMS-DU).** Two AMS units milking 140 cows twice daily.

**20 Unit MS CM Parlour (20MS).** 20 unit herringbone milking parlour, milking 140 cows with MS technology (batch feeders in the milking parlour, swing-over arms and automatic cluster removers).

**20 Unit HS CM Parlour (20HS).** 20 unit herringbone milking parlour, milking 140 cows twice daily with HS technology (individual electronic cow feeders, swing-over arms, automatic cluster removers, electronic milk meters, automatic identification, automatic drafting, automatic washer, automatic cluster cleaning between individual cow milkings and an electronic milk diversion line).

### 4.3.2 Moorepark Dairy Systems Model (MDSM) – Bioeconomic model

The MDSM is a stochastic budgetary simulation model of a dairy farm. It combines animal inventory and valuation, milk supply, feed requirements, land and labour utilization, and financial and economic analysis of the production systems (Shalloo et al., 2004). The model was developed to examine key aspects of Irish grass-based systems of production and was validated by comparing the results from the model against data collected from 21 CM Irish dairy farms. It provides the platform to assess the effects of varying biological, technical and physical factors on farm profitability. Since its development, the model has been used to assess technology investments (Upton et al., 2015a), varying pasture production systems (Patton et al., 2012) and farm
expansion strategies (Hutchinson et al., 2013, McDonald et al., 2013). The model was used in the current study to quantify the economic implications of investment strategies on farm profitability across two farm sizes. The on-farm labour and electricity data, together with the initial capital and maintenance costs associated with each milking system were integrated into the MDSM for the different milking systems.

4.3.3 Model assumptions

Financial and biological model assumptions are outlined in Table 4.1. Farm sizes of 28 ha and 56 ha for MF and LF, respectively, and a stocking density of 2.5 cows/ha was applied to each farm simulation. An annual milk production of 5,000 L/cow, concentrate supplementation input of 350 kg/cow, grass growth of 13 tonnes DM/ha and annual replacement rate of 18% were assumed across both farm sizes and all 3 milking systems. These assumptions are based on historical Irish data. Labour was valued at €12.50/hour, while an opportunity cost of land was included at €445/ha. Variable costs (concentrate feed, fertiliser, veterinarian fees, contactor charges, silage and reseeding), fixed costs (farm maintenance and running costs, car, telephone, electricity and insurance) and sales value (milk, cull cow, milking cow and calf) were based on current prices (Teagasc, 2014). A two tier pricing structure for electricity costs (based on the period of day at which electricity consumption occurred) was assumed at €0.08 and €0.18/kWh for night and day tariffs, respectively (SEAI, 2015). Milking equipment and farm infrastructure were depreciated over a 10 and 20-year period, respectively. The investments were financed over a 10-year period at an interest rate of 5%. A rate of 5% was used to represent cows unsuitable for AM. This figure was based on experiences observed when training cows to the AM systems in the set up period (Sonck, 1995, Koning, 2004, Jacobs and Siegfroid, 2012). These cows were sold as milking cull cows.
valued at a sale price of €1,000/cow and were replaced in the herd by heifers. This results in the AM systems having less mature herds in the initial years of the investment.

**Table 4.1** Financial and biological assumptions used in the Moorepark Dairy Systems Model

<table>
<thead>
<tr>
<th>Item</th>
<th>Financial assumptions</th>
<th>Biological assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk price (€/L)</td>
<td>0.30</td>
<td>Farm size (ha)</td>
</tr>
<tr>
<td>Price value protein : fat</td>
<td>2:1</td>
<td>Medium farm 28</td>
</tr>
<tr>
<td>Concentrate price (€/ton)</td>
<td>290</td>
<td>Large farm 56</td>
</tr>
<tr>
<td>Replacement heifer price (€/head)</td>
<td>1545</td>
<td>Herd size (cows/ha)</td>
</tr>
<tr>
<td>Cull cow carcass price (€/kg)</td>
<td>2.20</td>
<td>Medium farm 70</td>
</tr>
<tr>
<td>Milking cows unsuitable for AMS sale price (€/head)</td>
<td>1,000</td>
<td>Large farm 140</td>
</tr>
<tr>
<td>Male calf price (€/head)</td>
<td>50</td>
<td>Stocking density (cows/ha) 2.5</td>
</tr>
<tr>
<td>Opportunity cost of land (€/ha)</td>
<td>445</td>
<td>Milk production (L/cow) 5,000</td>
</tr>
<tr>
<td>Labour costs (€/h)</td>
<td>12.50</td>
<td>(kg milk solids/cow) 400</td>
</tr>
<tr>
<td>Electricity cost (€/kWh)</td>
<td></td>
<td>Concentrate fed (kg/cow) 350</td>
</tr>
<tr>
<td>Day tariff</td>
<td>0.18</td>
<td>Grass growth (tonne/ha) 13</td>
</tr>
<tr>
<td>Night tariff</td>
<td>0.08</td>
<td>Milking cows unsuitable for AMS (%) 5</td>
</tr>
<tr>
<td>Depreciation period (years)</td>
<td></td>
<td>Annual replacement rate (%) 18</td>
</tr>
<tr>
<td>Milking equipment</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Infrastructure</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Interest rates (%)</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
4.3.4 Model inputs

On-Farm Labour Input. Labour data was generated from an on-farm study where ten and seven conventional and automatic milking farmers, respectively, participated in a year-long labour study. This study involved recording of labour input data by farm operators for various defined farm duties across a range of different task categories. Data were collected between March 2014 and February 2015. All farm operators recorded the duration of the different tasks they performed throughout the day. Records were compiled on a smart phone application (developed by Acorn Labour, Co. Cork, Ireland) on 3 consecutive days on the third week of each month. The list of tasks for AM were; checking AM system data, fetching cows indoors, fetching cows outdoors, robot cleaning maintenance, alarms, grass allocation, other dairy tasks, other enterprise tasks and non-farm activity. Tasks for the CM system included; herding of cows pre- and post-milking, milking, milking plant and yard cleaning, grass allocation, other dairy tasks, other enterprise tasks and non-farm activity. The data was subsequently downloaded from the phone application to a cloud based server and then to a Microsoft Excel database. Data were checked monthly for abnormalities and individual farmers were contacted to clarify the circumstances surrounding any irregularity. Average herd size for the AM and CM farms were 105 (range 69-205) and 120 (range 70-160), respectively.

Statistical Analysis. Labour data were analysed using mixed procedure analysis (Proc Mixed) in SAS v9.3. Farm was taken as the independent unit for analysis and therefore the monthly measurement was treated as a repeated measure. The following model was used:
\[ Y_{ijk} = \mu + G_i + M_j + e_{ijk}, \]

where \( Y_{ijk} \) = dependant variable, \( \mu = \) mean, \( G_i = \) milking system group \((i = 1 \text{ to } 2)\), \( M_j = \) month \((j = 1 \text{ to } 12)\) and \( e_{ijk} \) = residual error term.

The best fit covariance model (using AIC) was used for the analysis and residual checks were made to ensure that the assumptions of the analysis were satisfied. Where appropriate, log transformation was used to correct non-constant variance and skew in the residuals. Transformed data was used to examine statistical significance, however mean values presented in this paper are taken from non-transformed data. A Tukey adjustment for multiplicity was used in making contrasts of means.

**Capital Investment, Maintenance and Running Costs.** Milking machine purchase prices and service costs for AM and CM were obtained from the list prices of the manufacturers and suppliers of each system (Table 4.2). However, taking into consideration the recent adoption of new AM machines in Ireland, service and maintenance were also established based on the real farm data costs from countries with established AM systems. In this case an in-depth report on annual maintenance and service costs in Denmark was used as a guide (Sorensen et al., 2013). Daily running costs with regard to detergent cleaning were calculated based on purchase price and recommended usage rate. Electricity consumption was recorded using a wireless monitoring system (supplied by Carlo Gavazzi (Carlo Gavazzi Automation SpA, Lainate, Italy)) across a number of AM and CM systems. Wireless WAN routers were used to transport the data from farm to research center, where Powersoft logging and recording software (Carlo Gavazzi Automation SpA, Lainate, Italy) calculated
cumulative energy used (kWh) at 15 minute intervals for each on farm electricity consuming process. Measurements were taken on four and forty-two AM and CM farms, respectively, between April 2014 and March 2015. Milk production data of these farms were obtained from the milk purchasing companies. This allowed a comparable metric (Watt-hours/litre) be used across both farm size and milking system.
Table 4.2 Initial machine and infrastructural investment costs and annual machine maintenance and running costs for three types of milking technology\(^1\) on two farm sizes, MF (medium farm) and LF (large farm)

<table>
<thead>
<tr>
<th></th>
<th>MF</th>
<th></th>
<th>LF</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AMS-SU</td>
<td>12MS</td>
<td>12HS</td>
<td>AMS-DU</td>
</tr>
<tr>
<td>Machine purchase costs (€)</td>
<td>115,000</td>
<td>34,000</td>
<td>95,000</td>
<td>195,000</td>
</tr>
<tr>
<td>Infrastructure costs (€)</td>
<td>40,000</td>
<td>70,000</td>
<td>70,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Milk Cooling and Storage Equipment (€)</td>
<td>19,500</td>
<td>19,500</td>
<td>19,500</td>
<td>22,500</td>
</tr>
<tr>
<td>Machine service and maintenance costs (€/year)</td>
<td>6,000</td>
<td>1,700</td>
<td>3,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Consumables (€/year)</td>
<td>2,400</td>
<td>1,600</td>
<td>3,000</td>
<td>4,800</td>
</tr>
<tr>
<td>Electricity use (W/L)(^2)</td>
<td>62</td>
<td>41</td>
<td>41</td>
<td>62</td>
</tr>
<tr>
<td>Electricity day tariff usage (%)</td>
<td>64</td>
<td>67</td>
<td>67</td>
<td>64</td>
</tr>
</tbody>
</table>

\(^1\)AMS-SU = single unit automatic milking system; 12MS = 12 unit medium specification conventional milking parlour to include automatic in-parlour batch feeders; 12HS = 12 unit high specification conventional milking parlour to include milk meters, electronic individual cow feeders, automatic identification, automatic cluster removers, automatic drafting, an electronic milk diversion line, automatic cluster cleaning between cow milkings and an automatic washer; AMS-DU = double unit automatic milking system; 20MS = 20 unit medium specification conventional milking parlour to include automatic in-parlour batch feeders and automatic cluster removers; 20HS = 20 unit high specification conventional milking parlour to include milk meters, electronic individual cow feeders, automatic identification, automatic cluster removers, automatic drafting, an electronic milk diversion line, automatic cluster cleaning between cow milkings and an automatic washer.

\(^2\) Watt-hours per litre of milk.
4.3.5 Financial metrics

Each AM investment option was evaluated in terms of net profitability, cash flow, discounted net profit and return on investment for the additional investment when compared to the CM system. All analysis was completed pre-tax annually and over the full 10-years of the investment.

Discounted net profit was included in the analysis in order to consider the time value of money, given that money decreases in value over time. This allowed the visibility of returns of each technology, over time, to be quantified. The discounted rate was set to 2.5% per annum for the 10-year period; this figure was decided on after evaluation of the consumer price index inflation rates in the Irish economy from 2000 to 2013. Total discounted net profit (TDNP) was calculated using equation 1 as:

\[
TDNP = \text{Sum} (\text{Annual net profit} \times \text{discount rate}).
\]  

[1]

Cash flow considers the ability of each milking system described to meet financial commitments given all of the cash incomes and outgoings on an annual basis. The net cash flow from each of the six scenarios equalled the cash receipts minus the cash repayments. A business may be highly profitable, yet fail, due to negative cash flows occurring during the initial years post investment.

Return on investment (ROI) is a financial performance measure of the efficiency of each technology investment scenario. In these calculations, the return on additional investment over the base level (MS) of investment is calculated by dividing the average
difference in net profit by the difference in investment for each investment scenario. Return on investment is described by equation 2 as:

\[
ROI = \left( \frac{\text{Net Profit investment} \times \text{Net Profit base} + (\text{Interest investment} \times \text{Interest investment base})}{\text{Investment} \times \text{Investment Base}} \right)
\]

[2]

where net profit = the pre-tax net profit and base refers to MS technologies.

Investment figures for all scenarios are presented in Table 4.2. The ROI is used in this analysis to provide a metric of how effectively each technology-investment scenario used capital invested to generate income over the base level of investment (Upton et al., 2015a).

4.3.6 Sensitivity analysis

Sensitivity analysis was completed to reflect reduced capital costs, higher labour costs, higher interest rates, and higher and lower milk prices.

The introduction of capital grant aid that is potentially available under the Dairy Equipment Scheme, operated by Department of Agriculture Food and the Marine in Ireland at a grant rate of 40% on AM and CM equipment, up to a maximum investment of €80,000, will reduce capital costs; any investment above this figure is not subject to the 40% grant. The 40% grant also applies to milk cooling/storage facilities.
Additionally, the effects of increased labour costs were examined by increasing the cost of labour from the €12.50/hour used in the base analysis to €20/hour. This reflects a future potential scarcity of on-farm labour which would result in increased labour costs. Increased interest rates above the base of 5%, by 2% to 7% on the borrowed capital were included in the analysis.

Finally, the effects of increased (+€0.05/L) and decreased (-€0.05/L) milk prices were tested through sensitivity analysis relative to the base price of €0.30/L.

4.4 Results

4.4.1 On-farm labour input

The total dairy labour input and the labour input for specific dairy related tasks averaged (hours/cow per year) across AM and CM farms are shown in Table 4.3. Total dairy labour input was significantly less ($P < 0.05$) on AM compared to CM farms, with AM farmers requiring 15.8 h/cow per year and CM farmers working 25 h/cow per year. The average daily time spent at total dairy labour input was 8.9 and 5.2 h/day throughout the 12 month recording period, for CM and AM farms, respectively. Reduced labour with AM can be attributed to significantly less time ($P < 0.001$) spent at the daily milking process. On average CM farmers spent 3 h/day (range 0.5-4.5) at the process of milking. Given the compact spring calving pattern of the farms, the duration of this task throughout the year had a similar profile to the dairy cow lactation curve, peaking in May at 4.3 h/day and decreasing towards the end of lactation. As milking with an automatic system does not require the farmer to be present at milking time, the AM process only consumed 0.7 h/day (range 0.2-1.1 h/day). This saving in labour associated
with the milking process, was partially counteracted by significantly \( (P < 0.001) \) more time being spent at grass allocation on farms with an AM system. AM farmers spent on average 0.4 h/day ensuring their cows were allocated the correct amount of grass in each grazing area. However, as the CM farmers were not dependent on the allocation of grass for optimum cow traffic (and had only one grass allocation to administer, rather than three), they only spent 0.1 h/day attending to grass allocation. Time at grass allocation was highest for the CM farms in spring (0.28 h/day), when it was the most challenging to optimize grass utilization in poorer weather conditions. Despite labour being reduced by 9.2 h/cow per year, daily end of work times were similar for each milking system, at 18:32 (h:min). However, daily start times were significantly different \( (P < 0.05) \) with AM farms starting work 50 minutes later than CM farms, at 7:55 and 7:05 (h:min), respectively.

### 4.4.2 Labour costs

When labour rates of €12.50/hour were applied to the data, overall reduction in labour resulted in a simulated lower labour cost on the AMS-SU and AMS-DU farms at €14,078 and €28,155, respectively, compared to CM farm costs of €22,179 and €44,357 for MF and LF, respectively (Table 4.3). When measured as a percentage of total costs of production for specific farm systems, the trends were similar; labour on AMS-SU and AMS-DU farms accounted for 11.2% and 12.8% of total costs, respectively, while labour on conventional milking farms with 12MS, 12HS, 20MS and 20HS accounted for 18.8%, 17.3%, 21.3% and 20.2% of total costs, respectively.
### Table 4.3
Average dairy labour input (h/cow per year) for combined and specific dairy tasks on farms milking with automatic milking (AM) and conventional milking (CM) systems

<table>
<thead>
<tr>
<th>Milking System</th>
<th>AM</th>
<th>CM</th>
<th>SE</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total dairy labour¹</td>
<td>15.8</td>
<td>25.0</td>
<td>3.00</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Milking process ²</td>
<td>2.1</td>
<td>8.1</td>
<td>0.83</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Grass allocation ³</td>
<td>1.2</td>
<td>0.3</td>
<td>0.11</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Other dairy tasks ⁴</td>
<td>12.5</td>
<td>16.6</td>
<td>2.55</td>
<td>0.27</td>
</tr>
</tbody>
</table>

¹Sum of all tasks associated with the running of the dairy enterprise
²Milking process on automatic milking farms was the sum of time spent at robot cleaning and maintenance, checking AM data, attending to alarms and fetching any overdue cows from paddocks; milking tasks on conventional milking farms was the sum of time spent at herding cows to and from milking, milking and yard and machine cleaning
³Task refers specifically to the process of daily grass allocation to cows in the grazing paddocks
⁴Tasks associated with the operation of the dairy enterprise (excluding milking and grass allocation) such as maintenance of buildings and machinery, machinery and office work, calf and replacement heifer rearing, veterinary treatment of animals, heat detection and artificial insemination, drying off cows and training of cows to milking system
Table 4.4 Effect of milking system type on annualized dairy farm output variables (10-year period after installation) for three types of milking technology on two farm sizes, MF (medium farm) and LF (large farm)

<table>
<thead>
<tr>
<th></th>
<th>MF</th>
<th>LF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AMS-SU</td>
<td>12MS</td>
</tr>
<tr>
<td>Milk produced (€)</td>
<td>118,582</td>
<td>119,263</td>
</tr>
<tr>
<td>Total receipts (€)</td>
<td>135,578</td>
<td>135,610</td>
</tr>
<tr>
<td>Variable costs (€)</td>
<td>51,113</td>
<td>50,259</td>
</tr>
<tr>
<td>Fixed costs (€)</td>
<td>50,541</td>
<td>50,355</td>
</tr>
<tr>
<td>Depreciation charges (€)</td>
<td>23,783</td>
<td>17,683</td>
</tr>
<tr>
<td>Total costs (€)</td>
<td>125,437</td>
<td>118,297</td>
</tr>
<tr>
<td>Net profit</td>
<td>9,963</td>
<td>17,133</td>
</tr>
<tr>
<td>Margin per cow (€)</td>
<td>142</td>
<td>245</td>
</tr>
<tr>
<td>Margin per ha (€)</td>
<td>356</td>
<td>612</td>
</tr>
<tr>
<td>Margin per kg milk solids (€)</td>
<td>0.36</td>
<td>0.61</td>
</tr>
<tr>
<td>Margin per L milk (c/L)</td>
<td>2.7</td>
<td>4.7</td>
</tr>
<tr>
<td>Labour costs (€)</td>
<td>14,078</td>
<td>22,179</td>
</tr>
<tr>
<td>Labour as a % of total costs</td>
<td>11.2%</td>
<td>18.8%</td>
</tr>
</tbody>
</table>

1AMS-SU = single unit automatic milking system; 12MS = 12 unit medium specification conventional milking parlour to include automatic in-parlour batch feeders; 12HS = 12 unit high specification conventional milking parlour to include milk meters, electronic individual cow feeders, automatic identification, automatic cluster removers, automatic drafting, an electronic milk diversion line, automatic cluster cleaning between cow milkings and an automatic washer; AMS-DU = double unit automatic milking system; 20MS = 20 unit medium specification conventional milking parlour to include automatic in-parlour batch feeders and automatic cluster removers; 20HS = 20 unit high specification conventional milking parlour to include milk meters, electronic individual cow feeders, automatic identification, automatic cluster removers, automatic drafting, an electronic milk diversion line, automatic cluster cleaning between cow milkings and an automatic washer
4.4.3 Profitability

Medium Farm. The annual and TDNP for MF and LF over a 10-year period are shown in Table 4.5. The highest TDNP was achieved with the 12MS milking system at €151,480, which was 74% higher than AMS-SU at €86,868. The lowest TDNP was achieved by the 12HS system at €60,241. This was 31% less than the intermediate profitability of the AMS-SU. The difference in profitability between the milking systems was the greatest in the years immediately after the initial investment, due to the higher interest and depreciation charges for the AMS-SU and 12HS parlours. In year one of the investment, AMS-SU was €8,102 less profitable than 12MS. However, in year 10, that difference had reduced to €4,740 as interest on the debt was reduced greatly.

Large Farm. The annual and TDNP for MF and LF over a 10-year period are displayed in Table 4.5. Trends for the LF are similar to those for the MF, with the 20MS displaying the greatest TDNP (€559,713). However, AMS-DU achieved a marginally lower TDNP at €449,277 than 20HS at €451,226. Although trends are similar for MF and LF, the reduction in TDNP associated with AM is less in percentage terms for the LF than the MF, at 20% and 43%, respectively. Again, similarly to MF, the AMS-DU was 26% less profitable than 20MS in year one of the investment period and this reduced to 15% by year 10.

4.4.4 Cash flow

A summary for annual and total discounted net cash flow (TDNCF) projections are presented in Table 4.5. Annual projected cash flow was positive for all investment scenarios across both farm sizes. Projections followed similar trends to profitability.
with the systems which were least capital intensive and least expensive to run (12MS and 20MS), yielding more cash to meet daily financial obligations. AM system had a reduced cash flow of 25 and 15% relative to the MS technologies in the MF and LF herd sizes, respectively. However, AM had a 27 and 2% greater cash flow relative to the HS milking options across MF and LF herd sizes, respectively.
Table 4.5 Annual (for 10-years after the investment) and total discounted net profit (€ with discounted net cash flow included in parentheses) for three types of milking technology\(^1\) on two farm sizes, MF (medium farm) and LF (large farm)

<table>
<thead>
<tr>
<th>Year</th>
<th>MF</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>AMS-SU</td>
<td>3,173</td>
<td>6,034</td>
</tr>
<tr>
<td>12MS</td>
<td>(15,733)</td>
<td>(17,603)</td>
</tr>
<tr>
<td>12HS</td>
<td>11,275</td>
<td>13,905</td>
</tr>
<tr>
<td></td>
<td>(21,789)</td>
<td>(23,677)</td>
</tr>
<tr>
<td>AMS-DU</td>
<td>37,812</td>
<td>42,248</td>
</tr>
<tr>
<td>20MS</td>
<td>(53,150)</td>
<td>(56,127)</td>
</tr>
<tr>
<td>20HS</td>
<td>51,380</td>
<td>55,530</td>
</tr>
<tr>
<td></td>
<td>(63,411)</td>
<td>(66,495)</td>
</tr>
</tbody>
</table>

\(^1\)AMS-SU = single unit automatic milking system; 12MS = 12 unit medium specification conventional milking parlour to include automatic in-parlour batch feeders; 12HS = 12 unit high specification conventional milking parlour to include milk meters, electronic individual cow feeders, automatic identification, automatic cluster removers, automatic drafting, an electronic milk diversion line, automatic cluster cleaning between cow milkings and an automatic washer;

AMS-DU = double unit automatic milking system; 20MS = 20 unit medium specification conventional milking parlour to include automatic in-parlour batch feeders and automatic cluster removers; 20HS = 20 unit high specification conventional milking parlour to include milk meters, electronic individual cow feeders, automatic identification, automatic cluster removers, automatic drafting, an electronic milk diversion line, automatic cluster cleaning between cow milkings and an automatic washer.
4.4.5 Return on additional investment (ROI)

The ROI of the additional investment associated with AM and HS technologies were examined across both farm sizes. The MS technology was considered as the baseline in technology (Table 4.6). The investment associated with the base (MS) was €123,500 and €197,500 for MF and LF, respectively. Irrespective of farm size, both AM and HS technologies had REDUCED ROI’s relative to the base (MS), at -11 and -12% for AMS-SU and AMS-DU, respectively, and -14% for 12HS and 20HS, respectively. This was primarily due to the higher cost of investment overall and lower financial returns associated with these technologies.

Table 4.6 Return on additional investment (%) above the base after the 10-year period for three types of milking technology on two farm sizes, MF (medium farm) and LF (large farm)

<table>
<thead>
<tr>
<th></th>
<th>Base (MS)</th>
<th>AMS</th>
<th>HS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF</td>
<td>0</td>
<td>-11</td>
<td>-14</td>
</tr>
<tr>
<td>LF</td>
<td>0</td>
<td>-12</td>
<td>-14</td>
</tr>
</tbody>
</table>

¹MS = medium specification conventional milking parlour to include automatic in-parlour batch feeders (and automatic cluster removers at LF), with 12 and 20 milking units at MF and LF, respectively; AMS = automatic milking system with a single unit and a double unit at MF and LF, respectively; HS = high specification conventional milking parlour to include milk meters, electronic individual cow feeders, automatic identification, automatic cluster removers, automatic drafting, an electronic milk diversion line, automatic cluster cleaning between cow milkings and an automatic washer, with 12 and 20 milking units at MF and LF, respectively
4.4.6 Sensitivity analysis

The impact of milk price, reduced investment costs and increased interest rates on the total farm profits are presented in Table 4.7.

Milk Price. Trends were similar to that of the base study, when milk price was either increased to €0.35/L or decreased to €0.25/L from €0.30/L, with all systems affected similarly. All three investment scenarios at MF level returned a negative TDNP at the lower milk price, with MS CM parlours demonstrating the greatest ability to withstand periods of low milk price.

Reduction in Capital Required for Milking Technology. The effect of reducing the capital required for milking equipment through the implementation of a 40% grant, up to a maximum of €80,000 was investigated. As the investment in an AMS-SU was substantially greater than that of a 12MS, it allowed for a greater reduction in the initial cost of the former. Consequently, the difference in TDNP between the two milking systems was reduced from 43% in the base scenario to 29%. As the three original investment scenarios at LF size were greater than €80,000, the introduction of the 40% grant on milking equipment had a reduced effect on the difference in profitability of the LF systems, as described in the base scenario. All three scenarios reduced the original capital requirement by an equal amount (€32,000), and hence reducing interest and capital repayments by similar amounts as well.

Increase in Labour Costs. The effects of increasing labour costs were examined by increasing the cost of labour from the €12.50/hour (used in the base scenario) to €20/hour. While reducing the profit of all systems, it had the greatest effect on the CM
systems. This increased the competitiveness of AM relative to the CM technologies on both farm sizes. On the MF, the differential in TDNP over the 10-year period between AMS-SU and 12MS reduced from €64,612 to €20,600. Increasing labour costs resulted in a negative TDNP for 12HS, after the 10-years examined. Increasing labour costs in the LF continued the trends observed previously, with 20MS achieving a TDNP of €323,822 which was 8% greater than the AMS-SU with a TDNP of €301,065, while 20HS displayed the least profit at €216,407.

**Increase in Interest Rates.** The effects of increasing interest rates from the 5% used in the base study to 7% were examined. Trends in TDNP remained consistent with those described previously, with MS CM technology displaying the greatest profit across the two farm sizes, at €69,655 and €118,347 greater than AM at MF and LF, respectively. While the AM system returned intermediate profitability at MF (€68,683), it resulted in the least profit at LF (€419,465). Increasing interest rates resulted in a reduction in competitiveness for AM when compared to MS CM technologies.
Table 4.7 The effect of milk price, capital costs, labour costs and interest rates sensitivity analysis on total discounted net profit for three types of milking technology\(^1\) on two farm sizes, MF (medium farm) and LF (large farm)

<table>
<thead>
<tr>
<th></th>
<th>MF</th>
<th></th>
<th></th>
<th>LF</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AMS-SU</td>
<td>12MS</td>
<td>12HS</td>
<td>AMS-DU</td>
<td>20MS</td>
<td>20HS</td>
</tr>
<tr>
<td>Milk price</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>€0.35/L</td>
<td>263,305</td>
<td>328,116</td>
<td>237,788</td>
<td>800,518</td>
<td>911,696</td>
<td>804,281</td>
</tr>
<tr>
<td>€0.25/L</td>
<td>-85,955</td>
<td>-22,418</td>
<td>-113,469</td>
<td>101,998</td>
<td>209,182</td>
<td>101,767</td>
</tr>
<tr>
<td>Milking equipment cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduced by 40% up to €80,000</td>
<td>125,558</td>
<td>177,153</td>
<td>99,042</td>
<td>488,141</td>
<td>597,322</td>
<td>489,907</td>
</tr>
<tr>
<td>Labour costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>€20/ h</td>
<td>13,579</td>
<td>34,179</td>
<td>-56,149</td>
<td>301,065</td>
<td>323,822</td>
<td>216,407</td>
</tr>
<tr>
<td>Interest rates</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7%</td>
<td>68,683</td>
<td>138,338</td>
<td>41,021</td>
<td>419,465</td>
<td>537,812</td>
<td>422,377</td>
</tr>
</tbody>
</table>

\(^1\)AMS-SU = single unit automatic milking system; 12MS = 12 unit medium specification conventional milking parlour to include automatic in-parlour batch feeders; 12HS = 12 unit high specification conventional milking parlour to include milk meters, electronic individual cow feeders, automatic identification, automatic cluster removers, automatic drafting, an electronic milk diversion line, automatic cluster cleaning between cow milkings and an automatic washer; AMS-DU = double unit automatic milking system; 20MS = 20 unit medium specification conventional milking parlour to include automatic in-parlour batch feeders and automatic cluster removers; 20HS = 20 unit high specification conventional milking parlour to include milk meters, electronic individual cow feeders, automatic identification, automatic cluster removers, automatic drafting, an electronic milk diversion line, automatic cluster cleaning between cow milkings and an automatic washer
4.5 Discussion

When evaluating investment in milking technology, it is important to consider the effect such an investment will have on the long-term profitability and availability of cash to the farm business and the return for the additional investment made, given all of the considerations involved. Previous studies have examined the business profitability from farm accounts of AM farms, and compared those of AM and CM farms, respectively, over a 1 to 3-year period (Bijl et al., 2007, Steeneveld et al., 2012), while others have used simulation models to examine changes in the profitability of AM systems as affected by key performance indicators of the dairy farm operation (Cooper and Parsons, 1999, Arendzen et al., 2000). Additionally, the decision regarding investment in AM can be analysed as a real options problem, whereby the uncertainty and irreversibility associated with an investment is taken into consideration (Engel and Hyde, 2003; Floridi et al., 2013;). Engel and Hyde (2003) found when using real options analysis, a farmers decision to invest in AM would be economically justified if a farmers CM system was 5-years or older.

However, a common theme among these studies is their focus on AM in high input confinement systems. Only Jago et al. (2006b) has investigated the economics of AM in a pasture-based system. The current study is the first within the context of a pasture-based system, to measure the effect of investing in AM technology on long-term profitability and availability of cash for the farm business, while also evaluating the returns from the increased capital investment associated with AM systems. This study encompasses both AM and traditional herringbone CM technology, currently the norm on dairy farms at both the MF and LF sizes.
4.5.1 Labour usage

Labour (both skilled and unskilled) availability is considered among the greatest challenges facing dairy farmers in expanding dairy industries (O’Brien et al., 2015). Previous studies are in agreement that the adoption of AM technology leads to a reduction in the requirement for labour, although the level of labour reduction is less clear, varying between 11 and 40% (Sonck, 1995, Mathijs, 2004, Bijl et al., 2007). Mathijs (2004) found that the reduction in labour, while averaging at 19% varied hugely by country, with the Belgium farmers reducing labour by 28%, while Danish farmers only reduced labour by 11%. Bijl et al., (2007) found that AM farms used significantly less full time equivalent (FTE) labour units than CM farms, at 1.45 compared to 1.87, respectively. The evaluation of labour in the majority of these studies has been based on retrospective survey responses from farmers estimating their time input, rather than through the capture of "real-time" data on-farm. O’Donovan et al. (2008) showed that the milking process accounted for 33% of total dairy tasks on Irish CM dairy farms, while the current study showed a similar proportion of labour associated with CM (32%), but the proportion associated with AM was just 13% of total labour input.

The 36% reduction in labour associated with AM as measured in this study largely represented the reduction in time associated with the milking process from 3 h/day with CM to 40 min/day with AM. This reduction in labour is a key motivator for farmers to adopt AM. A survey of early AM adopters in Australia by Kerrisk and Ravenhill (2010) found that farmers were frustrated with the quality of labour available, with farmers citing a history or on-going staffing problems as a reason for investing in AM. Subsequently, with a lack of available skilled labour, CM systems have to endure
variability of operators when the main operator requires assistance or short-term replacement.

As the number of CM farms in the current study were small, combined with the variation in the level of technology within milking parlours on the farms, it was not possible to establish what the potential labour saving associated with milking with HS relative to MS technology may be. Therefore, it should be noted that potential savings in labour associated with HS CM parlours such as automatic cluster removers, automatic washing, automatic drafting and automatic milk diversion have not been taken into consideration, and thus are a potential limitation of the study. In the cases of automatic parlour washing and automatic drafting, the respective technology allows the task to be performed simultaneous to the task that the operator is carrying out, while automatic cluster removers allow a single operator to handle a greater number of milking units (O’Brien et al., 2012a).

Taking into consideration the importance of grazing management to a pasture-based AM system, it is not surprising to see a threefold increase in time spent daily at grass allocation by AM farmers. However, this extra time associated with grass allocation does not counteract the savings in labour associated with the AM process. This increased time at grass allocation may lead to a greater level of pasture management, which would improve grass utilization and nutritive value (Macdonald, et al. 2008, McCarthy et al., 2016), while subsequently improving profitability (French et al., 2015).
4.5.2 Effect of milking system on profitability

AM is recognized as a capital intensive investment (De Koning, 2010). The AMS-SU and AMS-DU milking equipment were 3.5 and 3.0 times more expensive than 12MS and 20MS milking equipment scenarios, respectively. However, given the smaller area required to house an AM system relative to a herringbone parlour, capital required for milking building infrastructure was 45% less in the AM scenarios. When the overall investment in milking (equipment and infrastructure) is taken into consideration, the AMS-SU and AMS-DU required 41% more capital than MS CM systems. This additional requirement for capital associated with AM relative to the MS technologies resulted in reductions in pre-tax TDNP of €64,612 and €110,436 over the 10-year period for MF and LF herd sizes, respectively. This is a consequence of the greater interest, depreciation, energy and maintenance costs of AM even though labour costs were significantly lower. The differences in TDNP were greatest in the initial years of the investment. Similar to profitability, cash flow was reduced with AM by 25 and 15%, respectively, for MF and LF. While TDNCF was reduced, it did not result in negative cash flow in any of the 10-years investigated.

When compared to the equivalent technology in the HS parlour, AMS-SU and AMS-DU, while nearer in monetary terms, still required considerably more capital investment in the milking equipment than 12HS and 20HS, at 21 and 44%, respectively. Total capital investment in milking equipment and infrastructure varied from 5% less to 5% greater when AM and HS technologies were compared at MF and LF herd sizes, respectively. Despite the greater financial outlays, the reduced labour associated with AMS-SU, resulted in a 44% greater TDNP after 10-years for AMS-SU compared to 12HS technology at MF level. However, at LF AMS-DU was marginally (€1,949) less
profitable than 20HS after 10-years. This study showed that when compared with a herringbone parlour of HS technology at MF, the AM system has an increased TDNP and TDNCF, due primarily to the decrease in labour requirement. Thus, taking into consideration that the milking process on CM farms accounted for 32% of all dairy labour, the investment in HS parlours over AM is questionable, particularly at MF size, as it generates the least profit and the least surplus cash out of the investment scenarios examined at this farm size, while still maintaining a considerable labour requirement.

However, on farm decisions to install HS technologies are often based on a range of factors that are difficult to quantify, such as benefits in the management of labour, operator health and safety, lifestyle and herd health, all which may be as persuasive as the economics. While a high return on capital may not be provided by technology, the technology has the potential to provide milking operators with enhanced comfort and reduced fatigue (Tarrant and Armstrong, 2012). O’Donovan (2008) observed the need for the operator to remain in the parlour pit for optimum milking efficiency, thus requiring the presence of automatic drafting. Ohnstad et al. (2012) found that while capturing labour saving with automation can be difficult, automating the components of the milking process did lead to a more structured milking routine, which may have additional benefits in terms of mastitis prevention and control. Automatic cluster removers have a particular role to play in preventing the possibility of over milking, which may otherwise lead to thickening of the skin at the teat end (Österas and Lund, 1988) and increasing the teat end to the exposure of infection causing bacteria (O’Brien et al., 2012a). Additional to this, it is difficult to ascertain the value of the additional information provided by the HS technologies, such as individual cow milk yield. The regular availability of this data combined with additional animal health benefits, may
lead to greater discretionary culling of underperforming cows and subsequently improved herd performance. Thus, any decision to invest in CM HS technologies will need to assess not only the economic impact, but also the desired operator working environment and potential animal health benefits.

4.5.3 Effect of labour and capital costs on profitability

Lightfoot and Mulvany (2002)) noted that AM could become economically viable, in the context of the Australian dairy industry, if the price of units decreased by 25%, and if the cost of labour increased to AUS$20/hour. When the investment cost was reduced in the current study, it had some positive impact at the MF size, but had little effect on the difference in profitability between the scenarios at LF. When the cost of labour was increased to €20/h in the current study, the difference in TDNP between AM and MS CM changed from €64,612 and €110,437 for MF and LF, respectively, to €20,601 and €22,757, respectively. Thus when the cost of labour increased, AM increased in competitiveness and profitability relative to MS technology, particularly at the larger herd size. (Rotz et al. (2003) established that relatively small changes in wages for milking labour, such as 20%, had little impact on profitability, but when the value of milking labour was doubled it made AM more easily justified. In the context of the current study, the combination of both increased labour costs for all milking systems and reduced AM capital costs, resulted in AM having a greater (+€11,100) and similar (-€1,500) TDNP relative to MS technology, at MF and LF, respectively.

However, irrespective of farm size it is important to consider whole-farm profitability, particularly for farms that do not employ labour (thus the farm profitability and labour costs combined). While the AM system is associated with reduced labour requirement,
if this labour was not hired before the introduction of AM (family labour) the farmer does not benefit in terms of reduced labour costs through the introduction of an AM system. In these situations there are no monetary gains to the farmer from reducing the requirements for labour and thus, the farmer’s disposable income will be reduced by the savings in labour and the reduction in profitability reported in the current study. This diminishes the competitiveness of AM, as although the CM farmer is working more hours, in real terms the financial return is greater, with the AM farmer losing the difference in labour costs as well as profit. However, if the incentive in investing in an AM system is to reduce the labour requirement of the farmer, then it will achieve that objective. Then the investor prioritizes reduced labour and improved lifestyle choices over maximizing financial return.

4.5.4 Machine running and maintenance costs

Running and maintenance costs were higher for the AM system. This was not unexpected given the magnitude of electronics and mechanics associated with AM compared to MS milking technology. A Danish report (Sorensen et al., 2013) on the maintenance and service costs of 52 AMS farms (units installed between 1999 and 2011) found a large disparity in service and maintenance cost between farms. Average costs were €8,000 per AM unit, ranging from €2,500 to €13,400 per robot. While a correlation was not found between the maintenance costs and the number of milkings per robot, maintenance and service costs at the higher end of the spectrum may result in a prolonged machine life, due to a high annual replacement rate of parts. This type of information is not quantifiable in Ireland as of yet, with the vast majority of AM units installed in recent years. However, Steeneveld et al. (2012) concluded that the greater replacement rates of components of AM, in turn leads to the higher service and
maintenance cost associated with AMS in the short term. Findings in the current study showed that electricity consumption, when measured in terms of watts/litre of milk was 50% higher with AM. This was in agreement with the study of Upton and O'Brien (2013) which reported a 79% increase in electricity consumption with AM when comparing parlour types on a grass-based research farm. When day and night rate tariffs were applied to ascertain a monetary value, this equated to an increase of 58% in electricity costs. Due to the high level of technology involved, a shorter life time is generally assumed for AM systems (Cooper and Parsons, 1999, Hyde and Engel, 2002). However, due to the more recent uptake of AM in Ireland, there is little knowledge regarding the life span of AM units and therefore, this study assumes a minimum life span of 10-years for all three milking technologies investigated.

4.5.5 ROI and hurdle rate

The ROI calculation may be used to provide a robust approach to investment appraisal in relation to technologies over the useful life of the investment. The ROI, in coincidence with the minimal rate of return or hurdle rate, can be used as an appraisal metric to assist in the selection process of suitable investment options. A general guideline used in economic modelling is that an investment must return at least 3 to 7.5% above the costs of funds (Schall et al., 1978, Hayes and Garvin, 1982, Lang and Merino, 1993, Barker, 1999, Meier and Tarhan, 2007), which in the current study, would be 8 to 12.5% as the loan interest rate was 5%. This approach allows dairy farmers to appraise different investment options on farm while at the same time benchmarking potential investment on the farm against prospective investment that could be made outside of the farm. Based on the analysis completed in the current
study, the additional investment associated with AM, would never be justified when measured wholly on economic terms.

4.5.6 Additional considerations

While previous studies from high-input confinement AM systems have indicated production increases of 5-10% (De Koning, 2010), the AM systems examined in the current study were low-input systems that focus on the utilization of grazed grass, similar to the CM systems considered in the study. French et al. (2015) illustrated that every extra ton of grass DM/ha utilized increased farm profit by €267/ha. Ramsbottom et al. (2015) also contended that it is not the system with the greatest milk production that is most profitable, but the system with the lowest total costs. Thus, the most appropriate system in the Irish scenario is the low cost grass based system of milk production. However, if the AM technology were to be examined in the context of a grass-based system with higher levels of concentrate supplementation, the potential economic outcome may differ as a result of a more targeted feeding and milking approach of individual cows as in the studies of André et al. (2010a) and André et al. (2010b). Furthermore, the introduction of AM may lead to potential animal health benefits in the form of (a) reduced lameness as the cows are no longer herded from the pasture and instead walk at their own pace to the dairy and (b) reduction in cases of mastitis possibly contributed by the reduced transfer of bacteria from cow to cow during milking, less over milking and the early detection of potential mastitis cases from the milking robot generated data. Geary et al. (2012) demonstrated that reducing milk somatic cell count had the potential to increase net farm profit by 3.6 cents/kg of milk. Additionally, the availability of data on the individual cow at the each milking may lead to more selective breeding and culling of cows. Despite the potential benefits of such
information, it is difficult to establish the monetary value of such data to the farmer, as it is at the discretion of the individual what role the available data plays in supporting decision making on the farm.

With the removal of EU milk quotas and a proposed increase of 50% in milk output by 2020 (DAFM, 2010), dairy farmers will be looking to grow their businesses as cost effectively as possible. A study of 800 Irish dairy farms showed considerable underutilization of existing animals, land and labour with considerable scope for increased productivity (O'Donnell et al., 2008). Taking into consideration the average herd size of 64.6 cows of the farms surveyed by O'Donnell et al. (2008) and the proposed increase of 50% in milk output by 2020 (DAFM, 2010), AM would be an option for many of those farmers. Therefore, farmers will need to make decisions to take into consideration the key areas that will influence those decisions such as (a) farm growth using AM would require considerable investment in milking equipment and (b) the MS and HS CM technologies featured in the current study, have the potential to milk considerably more cows than presented, with no additional investment required in milking technologies, although additional labour would be required. This additional labour combined with the increased labour associated with CM, is a social cost to be considered, particularly as herds expand. Therefore, decision making regarding investment in new milking technology needs to encompass the desired workload of the individual, available skilled labour and the economic goals of the farm.
4.6 Conclusion

The objective of this paper was to identify the profitability over a 10-year period following an initial investment in an AM system relative to two specifications of CM technologies, across two farm sizes, in a pasture-based system. The results indicated that at both farm sizes, the investment in AM technology yielded less profit than MS CM technology, while similarly, investment in HS CM technology yielded less and similar profits than AM at a MF and at LF, respectively. Although the AM system was associated with greater interest and capital repayments, depreciation, maintenance and running costs and lower profitability, the lower labour associated with AM still make it an attractive lifestyle choice for some farmers. The analysis suggested that profitability should not be the reason for investing in AM technologies. Thus, any decision to invest in AM should consider a number of factors such as the availability of skilled labour, lifestyle sought by the farmer, interest in technology and the initial capital investment requirement by the milking system.
Chapter 5: The effect of concentrate supplementation on milk production and cow traffic in early and late lactation in a pasture-based automatic milking system

Animal 12:853 - 863
5.1 Abstract

The objective of this experiment was to establish the effect of low concentrate (LC) and high concentrate (HC) supplementation in the early and late periods of lactation on milk production and cow traffic in a pasture-based automatic milking (AM) system. Forty cows (10 primiparous and 30 multiparous) were randomly assigned to one of the two treatments. The experimental periods for the early and late lactation trials extended from 23 February to 12 April, 2015 and 31 August to 18 October, 2015, respectively (49 days in each trial period). The early lactation supplement levels were 2.3 and 4.4 kg/cow per day for LC and HC, respectively, while the late lactation supplement levels were 0.5 and 2.7 kg/cow per day for LC and HC, respectively. Variables measured included milking frequency, -interval, -outcome and -characteristics, milk yield/visit and per day, wait time/visit and per day, return time/visit and the distribution of gate passes. As the herd was seasonal (spring) calving, the experimental periods could not run concurrently and as a result no statistical comparison between the periods was conducted. There was no significant effect of treatment in the early lactation period on any of the milk production, milking characteristics or cow traffic variables. However, treatment did significantly affect the distribution of gate passes, with the HC cows recording significantly more gate passes in the hours preceding the gate time change such as hours 7 (P <0.01), 15 (P <0.05), 20, 21 (P <0.001), and 22 (P <0.05), while the LC treatment recorded significantly more gate passes in the hours succeeding the gate time change, such as time points 2 (P <0.01) and 10 (P <0.05). There was a significant effect of treatment in late lactation, with HC having a greater milk yield (P <0.01), milking duration and activity/day (P <0.05), while also having a significantly shorter milking interval (P <0.05) and return time/visit (P <0.01). The distribution of gate passes were
similar to the early lactation period, with HC also recording a significantly greater number of gate passes during the early morning period \((P < 0.01)\) when visitations were at their lowest. Any decision regarding the supplementing of dairy cows with concentrates needs to be examined from an economic perspective, to establish if the milk production and cow traffic benefits displayed in late lactation outweigh the cost of the concentrate; thereby ensuring that the decision to supplement is financially prudent.
5.2 Introduction

The commercialisation of automatic milking (AM) systems has provided an alternative milk harvesting method to the labour intensive process of conventional batch milking. Factors such as the unsociable nature of milk harvesting and a deficit in the availability of skilled labour, has led to increasing adoption of the technology at farm level. However, initial installations of AM systems were limited to countries where dairy production is characterised by intensive indoor housing systems. This is primarily due to the fact that AM systems were originally developed for use in such production systems, which are dominated by high costs of production and high yielding cows (Lind et al., 2000).

The integration of AM and pasture-based systems was not considered feasible until reported by Greenall et al. (2004) and Jago et al. (2004). This development, combined with an increasing body of research on the factors affecting AM system optimisation in pasture-based systems (Jago et al., 2006c, Lyons et al., 2013c, Scott et al., 2014; among others), has allowed adopters to make more informed decisions with regard to the combination of AM and grazing. This focus on AM and grazing is timely, as there is a renewed focus on the benefits of grazing; one of the main benefits of which is its comparative advantage of reducing total cost of production (Dillon et al., 2005). McCarthy et al. (2007b) also outlined the reduced profitability of systems of higher concentrate input relative to systems which rely on high quality grazed grass. Thus, systems of milk production which utilise large quantities of grazed grass are substantially more insulated against periods of low milk price or high cereal costs (Dillon et al., 2005, McCarthy et al., 2007b, Patton et al., 2012). These benefits at farm
level are added to by the superior quality of the milk product produced by pasture fed cows (O’Callaghan et al., 2016). Furthermore, the green image associated with cows grazing pasture continues to appeal to consumers, resulting in potential new markets for products.

“Seasonal production systems”, such as those operated in Ireland, New Zealand and Australia are established in such a manner as to maximise the utilisation potential of grazed grass, through aligning the start of calving with onset of pasture growth (Dillon et al., 2005). However, as the name suggests, the nature of grass growth is seasonal due to the prevailing climatic conditions which leads to grass deficits in the early and late lactation periods (spring and autumn, respectively). This, therefore, necessitates the judicious use of concentrate supplements during these periods, when grass growth levels are sub-optimal and not sufficient to meet herd demands. Not alone can supplementation be used as a tool to extend the grazing rotation, it can also be used to ensure the cow is offered sufficient energy in the diet (McEvoy et al., 2008), as the dry matter intake (DMI) of the dairy cow is at its lowest in the early lactation period (Ingvartsen and Andersen, 2000). This reduced DMI can result in cows experiencing energy expenditure greater than energy intake, also known as negative energy balance (Berry et al., 2006). However, Kendrick et al. (1999) established that cows on diets of higher energy density returned to positive energy balance sooner than those on diets of lower energy density. Thus, concentrate supplement can be used to maintain energy balance and increase total DMI of dairy cows (Delaby et al., 2001) in early lactation (Bargo et al., 2003).
The level of supplement offered will depend on the dearth of grass quantity. McEvoy et al. (2008) found that where grass availability was not limited in the early lactation period, that 3 kg/cow per day was an adequate level of supplement to meet nutritional and intake requirements of the dairy cow. When grass growth exceeds the demand of the herd, as is the case during the summer months, supplementing with concentrate is questionable as the milk response is limited (Kellaway and Harrington, 2004) and the substitution rate is increased (Bargo et al., 2002). Kennedy et al. (2003) also concluded that meeting the energy requirements of high yielding cows from a pasture only diet presents a significant challenge, which may result in such cows failing to achieve their true milk production potential. These factors have altered breeding strategies in pasture-based dairy systems in recent years, focusing on the breeding of smaller cows of higher durability. These cows have the potential to meet a greater proportion of their needs from grazed grass, thus, reducing the need to supplement with concentrate. However, in late lactation it is recommended to supplement with concentrate in order to maintain milk production and milk lactose content above a threshold at which milk becomes unsuitable for processing (O'Brien, 2008), as seasonal production systems present the challenge of low milk production in late lactation. Additionally, grass quality tends to decline as the year progresses, with autumn representing the period of lowest grass quality (McCarthy et al., 2013 and 2016). Reid et al. (2015) outlined that there was no difference in milk production from feeding 3 kg or 6 kg concentrate/cow per day in late lactation.

The successful operation of a pasture-based AM system relies on cows voluntarily trafficking from grazing at pasture to the milking yard and subsequently, back to pasture again. Without voluntary traffic, milking events will not be distributed evenly
throughout the day and failure to achieve this voluntary and distributed milking regime daily may have a negative effect on the uptake and adaption of AM technology at farm level (Lyons et al., 2013d). Jago et al. (2006c) established that stage of lactation affects the prolificacy of visitations to the milking yard, with late lactation cows trafficking to the milking yard less often than early lactation cows. Likewise, upon trafficking to the yard those same late lactation cows had a longer transit time from leaving pasture until presentation at the selection gate than the early lactation cows.

The objective of the current experiment was thus, to establish the effect of two differing levels of concentrate supplementation, in the early and late lactation periods, on milk production and cow traffic parameters in a seasonal calving pasture-based AM system.

5.3 Materials and Methods

5.3.1 Experimental description

The experiment was conducted at the Dairygold Research Farm, Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland (50°07'S, 8°16'W). The Moorepark soil type is described as a free-draining brown earth soil of sandy loam to loam texture. The farm-let area was a permanent grassland site, of predominately perennial ryegrass sward (*Lolium perenne* L.). Cows were milked using a Fullwood Merlin 525 AM unit (Fullwood Ltd, Ellesmere, United Kingdom).

Forty spring-calving dairy cows (10 primiparous and 30 multiparous) were selected from the Teagasc Moorepark AM herd. The experimental periods for the early (18.9 ± 8.54 days in milk (DIM)) and late lactation trials (207.9 ± 8.54 DIM) extended from 23
February to 12 April, 2015 and 31 August to 18 October, 2015, respectively (49 day trial period in each experiment). The experiment was a complete randomised block design with cows blocked based on breed, parity, DIM and pre-experimental milk yield, milking frequency and live weight. Cows had a predicted transmittable ability for milk production of +10 kg relative to the Irish economic breeding index base cow. Cows were randomly assigned to one of two possible flat rate feeding concentrate supplementation levels: (1) a low concentrate (LC) supplementation level where cows were offered 2.3 and 0.5 kg/cow per day in early and late lactation, respectively; or a high concentrate (HC) supplementation level where cows were offered 4.4 and 2.7 kg/cow per day in early and late lactation, respectively. Cows were retained on the same treatment (LC or HC) in late lactation as they were assigned to in early lactation. Non-trial cows were allocated 3 and 0.5 kg/cow per day in early and late lactation, respectively. The level of concentrate used within the treatments in early and late lactation periods represented or closely mirrored the actual level of concentrates that are offered to spring calved pasture-based cows on commercial farms at those periods of lactation. This resulted in a 2 kg differential in concentrate offered between the LC and HC treatments in both early and late lactation. The concentrate level offered to the cows was set using Crystal Software (Crystal 0.44, Fullwood Fusion, Willem Alexanderweg 83, 3945 CH Cothen, The Netherlands). Cows received 85% of their 24 hour concentrate allowance during the first milking of that 24 hour period, while the remaining 15% of their daily allowance was allocated in the subsequent milking(s). This ensured that cows milking less than two times per day consumed an adequate proportion of their concentrate allowance each day. The rate at which concentrates were dispensed in the AM unit (grams/second) were altered between treatment groups to ensure that
cows on differing levels of concentrates were receiving concentrates for a similar duration during their respective milking events.

5.3.2 Animal management

From calving until commencement of the experiment in early lactation, all cows were allowed full time access to pasture and 3 kg concentrate/cow per day. All cows were calved a minimum of seven days prior to trial start in early lactation, were familiar to the farm layout and were well conditioned to milking and trafficking in the pasture-based AM system. Each experimental period consisted of a seven day adjustment period, a seven day control period and a 35 day data collection period. As it was a seasonal calving system, the ratio of cows:AM unit varied in early and late lactation, as non-trial cows were calving onto the AM system in the early lactation, while the entire herd was milking and trafficking on the system in late lactation. Thus, cows had different milking permissions during both periods, which were implemented using the Crystal Software. Cows in early lactation were allowed a milking permission of three times per day (minimum milking interval of 8 hours), while cows in late lactation were allowed a milking permission of two times per day (minimum milking interval of 12 hours). Therefore, if a cow trafficked to the milking yard prior to an 8 or 12 hour lapse since her last milking event in early and late lactation, respectively, she was denied access to the robot by a pre-selection drafting gate. The cow was then directed to a post-selection gate where she was sent back to pasture. After the completion of the first experimental period (early lactation) all cows had their milking permission reduced to two times per day, at which they remained until dry-off. Additionally, all cows had their daily concentrate allowance reduced to 0.5 kg until the commencement of the late
lactation experimental period when the respective LC and HC treatments were applied to the trial cows.

5.3.3 Grazing management

Treatment groups and non-trial cows grazed as one herd of cows (40 trial cows and 40 non-trial cows), without any physical separation. The experimental grazing area consisted of 25.2 ha, divided evenly into three grazing blocks (A, B and C), with 15 individual paddocks in each grazing section separated by permanent fences. The average distance that cows had to walk from the yard to a paddock was 325 metres (range 25-650 metres). Cows were allowed access to each grazing section for eight hours; block A from 0000 h – 0800 h, block B from 0800 h – 1600 h and block C from 1600 h – 0000 h. Once access to a grazing section had closed no further cows were allowed into that section; however, cows who were already present in that grazing section were allowed to remain in there until leaving that section voluntarily. Cows who did not leave the paddock voluntarily were subsequently fetched prior to the opening of the next grazing allocation. The farm was walked weekly to assess farm pasture cover through visual estimation. Paddocks which were deemed to have a pasture cover greater than target were removed from the grazing rotation and harvested for silage. Cows were strip-grazed within each paddock, with cows receiving a new strip in each section over each 24 hour period. The size of the area allocated to the herd was determined by (i) the number of cows in the herd, (ii) the estimated grass intake of the herd (estimated total intake – concentrate supplement/three (grazing sections)), and (iii) the pre-grazing herbage mass. The pre-grazing herbage mass (>4 cm) was determined twice weekly by cutting two strips of grass per paddock (1.2 m × 10 m) using an Etesia mower (Etesia UK Ltd., Warwick, UK). Ten measurements of compressed sward height were taken.
pre- and post-cutting using a rising plate meter (diameter 355 mm; Jenquip, Feilding, New Zealand). All mown grass from each cut was weighed and then a sample was collected. A subsample of 0.1 kg was dried at 90°C for 16 hours for DM estimation. Pre- and post-grazing sward height was assessed daily using a Jenquip rising plate meter. Pre- and post-grazing sward heights were measured by taking 30 measurements/grass allocation per day.

5.3.4 Chemical analysis
A composite sample of grass was formed from the two strips of grass cut in each paddock prior to grazing. These samples were frozen at -20°C and at the end of each grazing rotation the samples were bulked by bowl chopping them. Samples were subsequently freeze dried for 48 hours, milled though a 1mm sieve and stored for chemical analysis. They were then analysed for contents of ash, ADF, NDF (ANKOM™ technology, Macedon, NY, USA; (Van Soest et al., 1991)), CP (Leco FP-428; Leco Australia Pty Ltd., Baulkham Hills, New South Wales, Australia) and organic matter digestibility (OMD; Fibertec™ Systems, Foss, Ballymount, Dublin 12, Ireland; (Morgan et al., 1989)). The concentrate offered was sampled each week and analysed using near infrared reflectance spectroscopy (NIRS; Foss-NIR System DK, Hillerød, Denmark) for DM, CP, NDF, ash and crude fibre.

5.3.5 Data description
Cows were fitted with a leg mounted radio transponder identification device (Afitag, Afimilk, Kibbutz Afikim, 1514800, Israel) that allowed automatic identification at the pre- and post-selection gates and in the milking unit. Thus, data from both the selection gates and the AM system were recorded electronically. Data recorded by the AM
system included cow number, milk yield/milking and per day (kg/cow), number of milking/day, milking interval (hours/cow), milking duration (minutes/cow), average quarter dead time (seconds/cow), average milk flow rate (kg/min) and concentrate consumed (kg/cow). At the conclusion of each milking event, that milking event was assigned one of three possible outcomes; successful, yield carry over (YCO) or failure, according to the actual yield of milk produced relative to the expected yield. A milking was deemed successful when >80% of the expected yield was harvested; a YCO was defined as when >20% and <80% of expected yield was harvested, while a failed milking occurred when <20% of expected yield was harvested. After a failed milking, the cow was returned to the milking yard for another attempt at milking. A YCO milking also resulted in an earlier admission (than permitted by the milking permission setting) of that cow to the milking robot for the subsequent milking, with the timing of re-entry determined by the proportion of milk harvested in the previous milking. All data concerning milking parameters excluded failed milkings since these cows were automatically returned to the pre-milking waiting yard for another milking. The recording of the passing of each individual cow at the selection gates by Logview software (Fullwood Ltd, Ellesmere, United Kingdom) allowed for the calculation of cow traffic variables. These included return time (time, in hours, elapsed from when a cow exited the post selection gate until she returned to the pre-selection gate) and wait time (time, in hours, elapsed from when a cow entered the pre-milking yard until she entered into the AM unit). The variable return time represented the average of return times associated with each individual visit to the milking yard, whereas wait time was averaged for each individual visit and summed for each 24 hour period to get a daily wait time value. Data on the number of pre-selection gate passes by the cows in each treatment group were also recorded on an hourly basis. Activity minutes were measured
using the leg mounted radio transponder which also acted as a pedometer. Pasture data collected each day included pre-grazing sward heights, area of pasture allocation and post-grazing sward heights.

5.3.6 Statistical analysis

Data were statistically analysed using least squares means ANOVA using mixed procedure analysis (PROC MIXED) in SAS v9.3 (SAS Institute Inc., Cary, NC, USA). Both experimental periods were analysed separately. Cow was included as the random effect and weekly measurement was treated as the repeated measure. Data from the control week was included as the covariate for each dependent variable. The following repeated measures mixed model was used for the variables: milking frequency, milking interval, milk yield/milking and per day, milking duration/visit and per day, average milk flow, quarter dead time, activity/day and return time/visit, wait time/visit and per day:

\[ Y_{ijklmno} = \mu + PV_i + T_j + B_k + P_l + D_m + C_n + Wo + TiBk + TiPl + TiWo + e_{ijklmno} \]

where \( Y_{ijklmno} \) is the dependent response variable, \( \mu \) is the overall mean, \( PV_i \) the pre-experimental variable used as the covariate, \( T_j \) the treatment \( j \), \( B_k \) the breed \( k \), \( P_l \) the parity \( l \), \( D_m \) days in milk \( m \), \( C_n \) the random effect of cow \( n \), \( Wo \) the repeated measures effect of week \( O \), \( T_iB_k \) the interaction between treatment and breed, \( T_iPl \) the interaction between treatment and parity, \( TiWo \) the interaction between treatment and week, and \( e_{ijklmno} \) the residual error term.
The covariance structure of models were tested and the selection among autoregressive (1), heterogeneous autoregressive (1), compound symmetry, heterogeneous compound symmetry and unstructured covariance structures were determined based on the lowest Akaike's Information Criterion and Bayesian Information Criterion (Littell et al., 2006). The Kenward-Rogers method was used for the calculation of degrees of freedom for all mixed models. Significance was set at 5% ($P < 0.05$), with non-significant effects removed from the models by backward elimination. Significance was examined by post hoc analysis of means using a Tukey-Kramer test. The milking event outcome proportions were pooled by treatment and analysed using the logistics procedure (PROC LOGISTIC) of SAS. The daily distribution of pre-selection gate passes were pooled by treatment and analysed using frequency procedure (PROC FREQ) of SAS. Significance for $\chi^2$ test were used to test between treatment groups in relative frequency of gate passes at any particular time point.

5.4 Results

5.4.1 Grazing and dietary characteristics

Mean grazing characteristics and grass quality are outlined in Table 5.1. Cows were allocated a total of 13.7 and 18.0 kg DM/ha of grazed grass in early and late lactation, respectively.
Table 5.1 Grazing and grass quality characteristics during the early and late lactation experimental periods

<table>
<thead>
<tr>
<th></th>
<th>Early</th>
<th>SD</th>
<th>Late</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-grazing herbage mass &gt;4 cm (kg DM/ha)</td>
<td>1349</td>
<td>315.7</td>
<td>1949</td>
<td>250.4</td>
</tr>
<tr>
<td>Pre-grazing sward height (cm)</td>
<td>9.2</td>
<td>1.32</td>
<td>13.7</td>
<td>0.84</td>
</tr>
<tr>
<td>DHA (kg DM/cow)</td>
<td>13.7</td>
<td>2.72</td>
<td>18.0</td>
<td>2.05</td>
</tr>
<tr>
<td>Post-grazing sward height (cm)</td>
<td>4.4</td>
<td>0.50</td>
<td>5.3</td>
<td>0.38</td>
</tr>
<tr>
<td>CP (g/kg DM)</td>
<td>231</td>
<td>23.6</td>
<td>218</td>
<td>31.7</td>
</tr>
<tr>
<td>ADF (g/kg DM)</td>
<td>258</td>
<td>27.1</td>
<td>272</td>
<td>21.5</td>
</tr>
<tr>
<td>NDF (g/kg DM)</td>
<td>397</td>
<td>33.1</td>
<td>403</td>
<td>32.0</td>
</tr>
<tr>
<td>OMD (g/kg DM)</td>
<td>827</td>
<td>23.8</td>
<td>825</td>
<td>21.1</td>
</tr>
<tr>
<td>Ash (g/kg DM)</td>
<td>111</td>
<td>16.9</td>
<td>113</td>
<td>24.1</td>
</tr>
</tbody>
</table>

Mean daily concentrate consumption in early lactation was 2.34 and 4.36 ± 0.03 kg/cow for LC and HC, respectively, while in late lactation LC and HC consumed 0.42 and 2.42 ± 0.02 kg/cow, respectively. Mean chemical composition of the concentrate offered is outlined in Table 5.2.

Table 5.2 Quality of the concentrate consumed during early and late lactation experimental periods

<table>
<thead>
<tr>
<th></th>
<th>Early</th>
<th>SD</th>
<th>Late</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM (g/kg)</td>
<td>923</td>
<td>0.9</td>
<td>924</td>
<td>1.5</td>
</tr>
<tr>
<td>CP (g/kg DM)</td>
<td>165</td>
<td>3.0</td>
<td>156</td>
<td>4.5</td>
</tr>
<tr>
<td>CF (g/kg DM)</td>
<td>127</td>
<td>2.2</td>
<td>167</td>
<td>8.1</td>
</tr>
<tr>
<td>NDF (g/kg DM)</td>
<td>318</td>
<td>6.9</td>
<td>438</td>
<td>9.7</td>
</tr>
<tr>
<td>Ash (g/kg DM)</td>
<td>52</td>
<td>1.8</td>
<td>55</td>
<td>2.6</td>
</tr>
</tbody>
</table>
5.4.2 Milking frequency, interval and outcome

Milking frequency, interval and outcome of the milking event for the early and late lactation experimental periods are outlined in Table 5.3.

**Early Lactation.** Concentrate supplementation level had no significant effect on milking frequency or milking interval. However, the outcome of the milking event was significantly affected. The HC treatment had a numerically lower milking interval than LC. This was likely a direct result of the HC treatment having significantly less successful milking events ($P < 0.01; 89.3$ and $84.4\%$ for LC and HC, respectively) and a significantly greater proportion of YCO's ($P < 0.01; 9.1$ and $12.5\%$ for LC and HC, respectively).

**Late Lactation.** Treatment had no significant effect on milking frequency. However, it did significantly ($P < 0.05$) affect milking interval, with the HC treatment having a $9\%$ shorter milking interval than the LC treatment, at $16.5$ and $18.2$ hours, respectively. This resulted in a numerically different milking frequency which, although not significant, was approaching significance with $P = 0.09$. Contrary to the early lactation period, it was the HC treatment which recorded a significantly greater and reduced number of successful ($P < 0.01$) and YCO ($P < 0.05$) milking events, respectively.

5.4.3 Milk yield and milking characteristics

Milk yield and milking characteristics for the early and late lactation experimental periods are outlined in Table 5.4.
Early Lactation. Supplementing with LC or HC in early lactation had no significant effect on milk yield or any of the milking characteristics considered. While not significant, the HC treatment did have a numerically greater milk yield per day while also having a numerically greater milking duration per day.

Late Lactation. Treatment had a significant effect on milk yield/day \((P < 0.01)\) and milking duration/day \((P < 0.05)\). High concentrate cows had a higher milk yield/day than LC cows (12.4 and 10.9 kg/cow, respectively), which resulted in a longer milking duration/day for the HC treatment of 8.6 minutes compared with 7.9 minutes for the LC treatment. The LC cows had a numerically lower milk yield/milking and numerically shorter milking duration/visit. Although not significant \((P = 0.67)\), the higher supplementation level resulted in a biologically shorter (-1.4 seconds) dead time/quarter compared with the cows on the lower level of supplement.
Table 5.3 The effect of low concentrate (LC) and high concentrate (HC) supplementation levels on daily milking frequency, milking interval and milking event outcome as a proportion of total milking events in early and late lactation

<table>
<thead>
<tr>
<th></th>
<th>Early</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LC</td>
<td>HC</td>
<td>SEM</td>
<td>P-value</td>
<td>LC</td>
<td>HC</td>
<td>SEM</td>
<td>P-value</td>
</tr>
<tr>
<td>Daily milking frequency/cow</td>
<td>1.8</td>
<td>1.8</td>
<td>0.05</td>
<td>0.99</td>
<td>1.3</td>
<td>1.4</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td>Milking interval/cow (hours)</td>
<td>13.3</td>
<td>12.6</td>
<td>0.45</td>
<td>0.22</td>
<td>18.2</td>
<td>16.5</td>
<td>0.67</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>% successful milking events</td>
<td>89.3</td>
<td>84.4</td>
<td>0.95</td>
<td>&lt;0.01</td>
<td>90.8</td>
<td>93.4</td>
<td>0.92</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>% YCO(^1) milking events</td>
<td>9.1</td>
<td>12.5</td>
<td>0.87</td>
<td>&lt;0.01</td>
<td>7.8</td>
<td>5.3</td>
<td>0.84</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>% failed milking events</td>
<td>1.6</td>
<td>3.1</td>
<td>0.43</td>
<td>0.15</td>
<td>1.4</td>
<td>1.3</td>
<td>0.39</td>
<td>0.82</td>
</tr>
</tbody>
</table>

\(^1\) YCO = Yield carry over
Table 5.4 The effect of low concentrate (LC) and high concentrate (HC) supplementation levels on milk production and milking characteristics in early and late lactation

<table>
<thead>
<tr>
<th></th>
<th>Early</th>
<th></th>
<th></th>
<th></th>
<th>Late</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LC</td>
<td>HC</td>
<td>SEM</td>
<td>P-value</td>
<td>LC</td>
<td>HC</td>
<td>SEM</td>
<td>P-value</td>
</tr>
<tr>
<td>Milk yield/day (kg/cow)</td>
<td>22.4</td>
<td>23.1</td>
<td>0.77</td>
<td>0.94</td>
<td>10.9</td>
<td>12.4</td>
<td>0.44</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Milk yield/milking (kg/cow)</td>
<td>13.1</td>
<td>13.3</td>
<td>0.47</td>
<td>0.41</td>
<td>8.7</td>
<td>9.4</td>
<td>0.42</td>
<td>0.11</td>
</tr>
<tr>
<td>Milking duration/visit (minutes)</td>
<td>7.8</td>
<td>7.9</td>
<td>0.28</td>
<td>0.89</td>
<td>6.3</td>
<td>6.5</td>
<td>0.19</td>
<td>0.24</td>
</tr>
<tr>
<td>Milking duration/day (minutes)</td>
<td>13.6</td>
<td>13.9</td>
<td>0.58</td>
<td>0.72</td>
<td>7.9</td>
<td>8.6</td>
<td>0.28</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Average milk flow (kg/minute)</td>
<td>1.7</td>
<td>1.7</td>
<td>0.05</td>
<td>0.85</td>
<td>1.4</td>
<td>1.4</td>
<td>0.05</td>
<td>0.82</td>
</tr>
<tr>
<td>Dead time/quarter (seconds)</td>
<td>23.2</td>
<td>22.0</td>
<td>1.37</td>
<td>0.46</td>
<td>30.2</td>
<td>28.8</td>
<td>3.27</td>
<td>0.67</td>
</tr>
</tbody>
</table>
5.4.4  *Cow traffic*

Results for cow traffic parameters for early and late lactation experimental periods are outlined in Table 5.5.

**Early Lactation.** Treatment had no significant effect on the cow traffic parameters analysed. Results were similar between treatments for return time/visit, wait time/visit and per day. However, numerical disparities ($P = 0.86$) existed between the treatments for activity, with the HC cows recording 37 minutes more activity/day than the LC cows.

**Late Lactation.** Supplementing with HC in late lactation significantly ($P < 0.01$) reduced the return time from pasture to the milking yard. Cows on the HC treatment returned from pasture 1.6 hours or 21% sooner than those on the LC treatment. Treatment also had a significant ($P < 0.05$) effect on activity, with HC cows recording 11% (52 minutes) greater activity than the cows on the LC treatment. Supplementation level did not influence wait time in the pre-milking yard on a visit or a daily basis.
Table 5.5 The effect of low concentrate (LC) and high concentrate (HC) supplementation levels on cow traffic and activity in early and late lactation

<table>
<thead>
<tr>
<th></th>
<th>Early</th>
<th></th>
<th></th>
<th></th>
<th>Late</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LC</td>
<td>HC</td>
<td>SEM</td>
<td>P-value</td>
<td>LC</td>
<td>HC</td>
<td>SEM</td>
<td>P-value</td>
</tr>
<tr>
<td>Return time/visit (hours/cow)</td>
<td>6.7</td>
<td>6.7</td>
<td>0.37</td>
<td>0.86</td>
<td>9.3</td>
<td>7.7</td>
<td>0.52</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Wait time/visit (hours/cow)</td>
<td>1.4</td>
<td>1.5</td>
<td>0.13</td>
<td>0.89</td>
<td>0.9</td>
<td>0.9</td>
<td>0.11</td>
<td>0.75</td>
</tr>
<tr>
<td>Wait time/day (hours/cow)</td>
<td>2.4</td>
<td>2.5</td>
<td>0.17</td>
<td>0.48</td>
<td>1.2</td>
<td>1.3</td>
<td>0.14</td>
<td>0.60</td>
</tr>
<tr>
<td>Activity/day (minutes/cow)</td>
<td>837</td>
<td>874</td>
<td>39.6</td>
<td>0.42</td>
<td>472</td>
<td>524</td>
<td>21.3</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>
5.4.5 *Gate passes*

Results of the distribution of pre-selection gate passes for the early and late lactation experimental periods are outlined in Figures 5.1 and 5.2. Figures 5.1(a) and 5.2(a) indicate the proportion of total gate passes occurring at each time point (each 1-hour interval) over the 24 hour period, for all cows participating on the trial. Figures 5.1(b) and 5.2(b) indicate the proportion of gate passes at each time point for cows on the different concentrate level treatments in early and late lactation, respectively.

**Early Lactation.** Concentrate supplementation level had a significant effect on the number of gate passes at seven of the 24 hour time points. LC had significantly more gates passes than the HC treatment at time points 2 \( (P < 0.01) \) and 10 \( (P < 0.05) \), while time point 13 was approaching significance \( (P = 0.06) \). However, HC had significantly more gate passes than LC at five out of the 24 time points measured, which included time points 7 \( (P < 0.01) \), 15 \( (P < 0.05) \), 20, 21 \( (P < 0.001) \), and 22 \( (P < 0.05) \), with time point 1 also approaching significance \( (P = 0.06) \).

**Late Lactation.** There was a significant difference between treatment groups for the number of gate passes at eleven of the 24 time points measured. Only one of these were accounted for by the LC treatment recording a significantly greater number of gate passes than the HC treatment, this occurring at time point 9 \( (P < 0.001) \). Thus, the remaining 10 time points represented a significant difference between treatments where the HC treatment recorded a greater number of gate passes then LC at that particular time point. These included time points 0, 8 \( (P < 0.05) \), 3 \( (P < 0.01) \), 4, 15, 19, 20, 21, 22 and 23 \( (P < 0.001) \).
Figure 5.1 (a) The combined total number of pre-selection gate passes for both treatments in the early lactation period, represented as an hourly proportion of the total. The time below each bar represents the hour that the gate passes occurred (i.e. bar 10 represents the gate passes that occurred between 1000 h - 1100 h).

(b) The effect of low concentrate (LC) and high concentrate (HC) supplementation levels in early lactation on the average hourly distribution of gate passes (gate passes/treatment as a percentage of total gate passes at each time point). The time below each bar represents the hour that the gate passes occurred (i.e. bar 10 represents the gate passes that occurred between 1000 h - 1100 h). Hours with significantly different throughput between treatments ($P < 0.05$) are identified accordingly (*). The vertical bar represents the average standard error of the difference.
Figure 5.2 (a) The combined total number of pre-selection gate passes for both treatments in the late lactation period, represented as an hourly proportion of the total. The time below each bar represents the hour that the gate passes occurred (i.e. bar 10 represents the gate passes that occurred between 1000 h - 1100 h).

(b) The effect of low concentrate (LC) and high concentrate (HC) supplementation levels in late lactation on the average hourly distribution of gate passes (gate passes/treatment as a percentage of total gate passes at each time point). The time below each bar represents the hour that the gate passes occurred (i.e. bar 10 represents the gate passes that occurred between 10:00 - 11:00 h). Hours with significantly different throughput between treatments ($P < 0.05$) are identified accordingly (*). The vertical bar represents the average standard error of the difference.
5.5 Discussion

In intensive indoor based AM systems, concentrate supplement is offered not only to increase milk yield, but also to increase milking frequency (Prescott et al., 1998), which will, in turn, have a positive effect on milk yield (Bach et al., 2007). However, the current experiment was conducted in the context of the low input seasonal pasture-based system, where the focus is on the harvesting and utilisation of grazed grass. Despite this focus on utilising large quantities of grazed grass, there remains the need to supplement with concentrate at certain periods of the lactation, due to reduced DMI or pasture supply. This usually occurs, but is not limited exclusively to, the early and late lactation periods, with the level of concentrate supplement offered being reflective of the availability of pasture.

5.5.1 Milking performance and characteristics

Treatment had no significant effect on milking frequency in either the early or late lactation period. This is similar to the findings of Jago et al. (2007) who investigated supplement level in a pasture-based AM system, and both those of Halachmi et al. (2005) and Bach et al. (2007) who studied the effect of supplement level in indoor AM systems. Although not statistically significant, the increase in milking frequency from 1.3 to 1.4 times per day with the high concentrate level in late lactation could be classified as approaching significance \((P = 0.09)\). As milking frequency is directly related to milking interval, the significant difference in milking interval between the LC and HC treatments was not unexpected.
The LC treatment achieved a significantly greater proportion of successful milking events than the HC treatment in early lactation, with this influencing the proportion of YCO milking events, since YCO cows were allowed access to the AM unit sooner than those recorded with a successful milking event. The reason(s) for these significant differences are unclear as observations of cow behaviour while in the milking unit were not undertaken. However, Prescott (1995) established that feeding during milking caused cows to move more in the milking unit, thus making the attachment of the cups more difficult, offering one possible explanation for the results observed in the current experiment. As both treatments received concentrate in the AM unit, it is possible that the level of concentrates offered may have influenced cow behaviour, as opposed to the concentrates themselves. The opposite was observed in late lactation with the LC treatment, this time receiving only 0.5 kg/cow per day in the AM unit, achieving a significantly reduced number of successful milkings. These findings concur with those of Jago et al. (2007), who found that a treatment receiving no concentrates in the AM unit had a numerically a lower proportion of successful milkings and greater proportion of YCO milkings. While the trends in milking event outcome differed between treatments across the early and late lactation periods of the experiment, it has become clear that a feeding level of 2 – 2.5 kg/cow per day achieved the greater proportion of successful milking events. Thus, this may indicate an interaction between feeding level and milking behaviour, something which warrants further investigation. Additionally, the impact of stage of lactation should not be discounted either, with the milk yield of the LC treatment reducing more rapidly over the duration of the late lactation experimental period compared to the HC treatment (18 and 8%, respectively; data not presented here).
Concentrate level had no significant effect on milk yield or any of the milking characteristics measured, such as milking duration, average milk flow or average dead time, in early lactation. The similar milk yield observed for the different treatments in early lactation may be a direct result of cows on the LC treatment mobilising more body reserves in the early lactation period (Bargo et al., 2002). Furthermore, Baudracco et al. (2010) outlined that due to the high energy content of spring grass, the milk response to concentrate was at its lowest during this period. As milk yield was not different between groups and as there is a positive correlation between milk yield and average milk flow (Weiss et al., 2004), average milk flow, dead time/quarter and average milking duration were not significantly different between treatments. This is an important finding in the context of seasonal AM production system where the calving is compact and aligned to the start of the grass growing season. This results in a large portion of the herd reaching peak milk yield together, which in an AM system puts substantial pressure on the AM unit at that period of the year. This may limit the potential number cows that can be milked and impact the overall optimisation of the system. However, due to the lack of an early lactation milk yield increase from feeding HC level and the subsequent lack of an impact on key metrics such as milking duration and average milk flow rate, the feeding of HC (should the need arise due to grass deficit) would not be detrimental to AM system optimisation at peak production, where the AM unit is operating at capacity.

However, in late lactation AM system capacity is not an issue in a seasonal production system as cows are at the lower end of their production cycle. During this period of the current experiment, the HC treatment (additional 2 kg/cow per day of concentrate) had a significant increase in milk production of 1.5 kg/cow per day. This may have been due to the quality of grass consumed by the cow, as a poorer quality base feed would result
in a greater milk response. McCarthy et al. (2016) outlined that spring grass (early lactation) has the greatest quality, while autumn grass (late lactation) has the poorest quality, as was the case in the current experiment. The milk response of 0.75 kg of milk per kg of concentrate in the current experiment is lower than that of Reid et al. (2015), who found a milk response of 0.96 kg of milk per kg of concentrate when moving from a grass diet with no concentrate supplementation to one with 3 kg of concentrate, in late lactation. However, that study was conducted in the context of a conventional milking system, where cows were milked twice daily. The reduced milking frequency of the cows in the current experiment would have equated to 4.2 less milking/cow per week than those in the study of Reid et al. (2015). Thus, it is possible that the reduction in late lactation milking frequency of the cows, herein, limited the ability of those cows to respond to the supplement allocated to them.

Due to the low degree of udder filling in late lactation (Bruckmaier, 2005), dead times and average milk flow did not differ significantly between the treatments. McCarthy et al. (2007a) established that cows on a HC diet in late lactation had a significantly greater average milk flow rate. However, unlike the current experiment, the cows in that experiment were of a higher genetic potential for milk production and were also on a higher level of concentrate supplement throughout the lactation and not only in the early and late lactation periods. The combination of the difference in milk yield and the similar average milk flow rates between treatments in the current study resulted in the HC treatment having a significantly longer milking duration/day. In a seasonal production system, this increase in milking duration in late lactation is not detrimental to the optimisation of the AM system, as there is a substantial surplus of capacity on the AM unit (depending on herd size) at that period of lactation.
5.5.2 Cow traffic and gate passes

The successful operation of an AM system, irrespective of production system, is dependent on cows presenting themselves at the milking unit on a voluntary and continuous basis. Jago et al. (2006c) established that cows in late lactation were less motivated to visit the AM unit than cows in earlier lactation. Although not statistically analysed, the current experiment is in agreement with the findings of Jago et al. (2006c), with late lactation cows having a numerically longer return time from pasture and lower activity levels than cows in early lactation. Interestingly, the results from the current experiment indicate that offering an additional 2 kg/cow per day of concentrate in late lactation had a positive impact on cow traffic with those cows returning from pasture 1.6 hours sooner than the LC cows. Jago et al. (2007) found that feeding concentrate during milking to early lactation cows provided little incentive for them to traffic from pasture to the dairy. Prescott (1995) outlined some reasons why cows are motivated to be milked, such as the discomfort caused by udder pressure, the gaining of a psychological reward for being milked and finally, that milk let down process is rewarding, due to the release of oxytocin. In the current experiment it is likely that the motivation of cows to milk was reduced in late lactation due to a lower level of milk production resulting in reduced udder discomfort relative to early lactation. Thus, the feeding of concentrate at the HC level had no effect in the early lactation period on return time, but did reduce return times from pasture in late lactation.

Treatment caused no significant effect on waiting times in the pre-milking yard, in either early or late lactation in the current experiment. This is at odds with the findings of Scott et al. (2014) who found that offering a small quantity of concentrate at milking reduced voluntary waiting times in the pre-milking yard. However, Lyons et al. (2013d)
indicated that data from Australia showed that the time taken to return from pasture to
the dairy was the main factor in explaining extended milking intervals. Therefore, while
it is important to reduce waiting time, it is of greater priority to reduce return time from
pasture in order ensure that extended milking intervals are reduced.

Treatments differed significantly in 7 and 11 of the one hour time point periods in early
and late lactation, respectively. With the pre-selection gate directing cows to a new
grass allocation in one of the three grazing sections at 0000 h, 0800 h and 1600 h, it was
expected that the largest proportions of pre-selection gate passes would occur at times
surrounding those time points. Time point 0 and 16 experienced large peaks, while the
traffic associated with the 0800 h gate change was more prolonged with traffic
distributed across a greater number of time points. In agreement with the literature, as
reviewed by John et al. (2016), there was a substantial decrease in the number of gate
passes in the early hours of the morning. The data from the current experiment indicated
that the cows on the HC treatment were visiting the milking yard in anticipation of the
pre-selection gate change, with the gate change representing not only the opportunity to
access the available of fresh grass, but also the opportunity to gain access to the AM
unit to receive their concentrate allowance. By moving from pasture to the yard prior to
the gate change, it allowed the cows gain access to the milking unit while also gaining
access to the fresh pasture early in the allocation, when there would have been large
quantities of leafy material still remaining. This was apparent in both early and late
lactation with significantly more gate passes at time point 7, 15 and 20-22 in early
lactation and significantly more gate passes at time points 8, 15 and 19 - 23 in late
lactation. In contrast, the LC treatment group visited the pre-selection gate significantly
more in the hours following the gate time change, such as time point 2 in early lactation
and time point 9 in late lactation. This may also indicate that the LC treatment cows were influenced by the movement of HC cows and if this were to be the case, it could be characterised as a possible limitation of the experiment, as both treatments grazed in the same pasture and milked in the same AM unit. However, even at the time points where no significance was observed, the LC treatment recorded a reasonable number of gate passes, indicating that although total gate passes for that treatment were lower, an even distribution of gate passes still occurred. In late lactation, the distribution of gate passes for the LC treatment group were more pronounced, not only following the pre-selection gate change but also during the day time period, with large troughs in the number of gate passes during the late evening and early morning periods. The dominance of the HC treatment during these periods of LC troughs indicated that the availability of concentrate supplement in the AM unit acted as motivation for cows to visit the yard during the periods of low occupancy. This finding concurs with the finding of Lessire et al. (2017), who found that although attendance at the AM unit was low at times such as the early morning period (0000 h – 0600 h), the cows that did attend were those receiving the higher level of supplement.

\[5.6\] Conclusion

This experiment examined the effect of supplementing dairy cows with two different levels of supplement in a pasture-based AM system, at a time when the inclusion of a supplement in the diet would be prevalent; in this case during the early and late lactation periods. Supplementing in early lactation with HC and LC levels, demonstrated no positive or negative effects on cow traffic or milk production. Nevertheless, in late lactation supplementing with HC resulted in increased milk production, a shorter
milking interval and a shorter return time from pasture. The higher supplement level also had the positive effect of bringing the cows to the milking yard at times of low occupancy, such as early morning. However, any decision regarding the supplementing of dairy cows with concentrates needs to be examined from an economic perspective, to establish if the milk production and cow traffic benefits displayed in late lactation outweigh the cost of the concentrate, thereby ensuring that the decision to supplement is financially prudent.
Chapter 6: The effect of dairy cow breed on milk production, cow traffic and milking characteristics in a pasture-based automatic milking system

Livestock Science 209:1 - 7
6.1 Abstract

Despite the increasing frequency of integrated automatic milking (AM) and pasture-based systems, there is limited knowledge available on the suitability of different dairy cow breeds to these systems. Thus, the objective of this experiment was to establish the performance of three breeds in a pasture-based AM system with respect to milk production, cow traffic and milking characteristics. The breeds examined were Holstein Friesian (HF), Jersey x HF (JEX) and Norwegian Red x HF (NRX), all of which have been previously identified as being compatible with conventional milking pasture-based systems. The experiment was conducted in mid-lactation and variables measured included milking frequency, interval, outcome and characteristics, milk yield/milking and per day, wait time/visit and per day, return time/visit and the daily distribution of milking events. Data were statistically analysed using least squares means mixed procedure models, while the proportion of different milking events were analysed using the logistics procedure. While there were no significant differences between breeds for milking frequency, or milk production, significant differences did exist for proportion of successful and failed milkings events, with NRX cows recording the highest and lowest proportions, respectively. JEX also recorded a significantly shorter dead time/quarter at 17.6 seconds/milking compared to the HF and NRX breeds at 28.5 and 27.7 seconds/milking, respectively. Significant differences also existed with regard to cow traffic, with the NRX breed returning from pasture more quickly and waiting a shorter time both per visit and per day in the pre-milking yard. The distribution of milking events differed between the breeds examined, with the JEX cows recording less milkings in the hour after the pre-selection gate changes of 0000 h and 1600 h. JEX also recorded a significantly greater proportion of milkings than the NRX and HF cows.
during the hours at which the lowest proportion of total milking events were recorded (0400 h – 0600 h). For the optimisation of the AM system it is important to have an even distribution of milkings throughout the day. Based on the evidence from the current experiment, this may be best achieved by a mixed breed herd rather than a single breed herd. However, the performance of the examined breeds should also be analysed in the context of the whole AM farm system, over an entire lactation, taking into consideration the range of variables that contribute to a profitable farm system.
6.2 Introduction

Automatic milking (AM) systems are becoming increasingly popular, with approximately 25,000 farms worldwide operating this type of milking system (Harms and Bruckmaier, 2016). The adoption of the technology at farm level has been motivated by a combination of factors such as lifestyle choices of individual farmers, reduced labour requirement associated with AM and difficulty attracting suitably skilled labour to dairy farms (Mathijs, 2004, Bijl et al., 2007, Shortall et al., 2016). Furthermore, the combination of AM and grazing, using initially two-way grazing (Jago et al., 2004) and subsequently three-way grazing (Lyons et al., 2013c), has allowed the adoption of AM in countries such as Australia, New Zealand and Ireland where grazing plays a key role in milk production. Due to animal welfare legislation, it is now also becoming increasingly more common for grazing to contribute various proportions of the dairy cow diet on farms in North Western Europe, which traditionally operated production systems where cows were indoors on an almost continuous basis. Increasing the proportion of grazed grass in such systems is challenging, with van Dooren et al. (2004) demonstrating a reduction in the proportion of grazed grass in the cows diet after the adoption of AM on dairy farms in the Netherlands. It is well documented that seasonal calving systems, where grazed grass forms the main component of the dairy cow diet, have a comparative advantage in reducing costs and increasing overall farm profitability (Dillon et al., 2005). Thus, it is vital in pasture-based farms that do adopt AM, that the utilisation and conversion of pasture into high value milk constituents is maximised. This conversion to milk is very much influenced by the suitability of the cow to (i) grazing and (ii) uneven milking intervals; both of which are influenced by cow breed.
The widespread use of Holstein-Friesian (HF) genetics to increase milk production potential (Harris and Kolver, 2001, Evans et al., 2006a) has ultimately compromised the fertility of the global dairy herd (Harris and Kolver, 2001, Norman et al., 2009), which is the cornerstone of all seasonal calving pasture-based production systems. Additionally, Kennedy et al. (2003) established that HF cows may not fulfill their genetic potential in pasture-based systems, as when these cows are on diets consisting of pasture only, they cannot consume sufficient energy to meet their requirements (Kolver and Muller, 1998). Such studies led to a focus on crossbreeding in order to establish a robust cow capable of meeting her energy requirements from a predominantly pasture-based diet (Buckley et al., 2005). Subsequently, Walsh et al. (2007) established the Norwegian Red breed as a highly suitable breed for crossing with the HF in pasture-based systems. Begley (2008) showed that Norwegian Red x HF (NRX) cows had a similar production potential and significantly improved reproductive performance and udder health compared with the HF, resulting in an increased profit of €143 per lactation compared to the HF.

With the removal of the EU milk quota regime, land will become the most limited resource on dairy farms. Combined with the introduction of a multi component payment system by milk processors in Ireland (Shalloo et al., 2007), dairy farmers are focusing on maximising milk solids production per hectare. These factors initiated an interest in crossbreeding HF cows with Jersey sires. Numerous international studies have examined the benefits of the subsequent Jersey x Holstein Friesian (JEX) offspring. In an Irish context, Prendiville et al. (2009) concluded that the JEX was an animal highly suited to grazing systems due to their high intake capacity at pasture, combined with the added benefit of improved production and feed efficiency. Furthermore, Coffey et al.
(2016) also established that the JEX was worth an additional €162 per lactation over the HF, due to superior milk production and reproductive performance. These results concur with those found on a global basis, showing JEX to have improved production (Penno, 1998), fertility (Auldist et al., 2007, Heins et al., 2008), intake capacity (Goddard and Grainger, 2004) and subsequently, improved profitability (Lopez-Villalobos et al., 2000). Furthermore, Clark et al. (2006) showed that milk yield of Jersey cows was not reduced with once daily milking to the same extent as that of HF. Additionally, the yield of milk solids from Jersey cows on once daily milking was maintained to a greater extent than that of HF cows. This could be a significant attribute in a pasture-based AM system.

However, little is known about the performance of these breeds in pasture-based AM systems, in particular with regard to cow traffic and ultimately how this will affect robot utilisation and efficiency, as highlighted by John et al. (2016). As voluntary cow traffic is the foundation on which successful AM operates, it is essential to develop an understanding on the suitability of different breeds to AM pasture-based systems. Thus, the objective of this study was to evaluate the HF, the NRX and the JEX breeds in a pasture-based automatic milking system, with regard to milk production and cow traffic.

6.3 Materials and Methods

6.3.1 Animal and experimental description

The experiment was conducted at the Dairygold Research Farm, Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland (50°07'N, 8°16'W), between April 20th and August 30th, 2015. Moorepark soil type is
described as a free-draining brown earth soil of sandy loam to loam texture. The farm-
let area was a permanent grassland site, of predominately perennial rye grass sward
(Lolium perenne L.).

Fifty spring-calving dairy cows (17 HF, 16 JEX and 17 NRX) were selected from the
Teagasc Moorepark AM herd. Thirty-five cows were multiparous and the remaining 15
were primiparous. Breed groups were balanced for parity, days in milk (DIM),
economic breeding index (EBI) and concentrate consumed per cow (kg) from calving
until start of experiment. The characteristics of the breed groups were as follows: HF
cows: parity 2.8 ± 1.1 (mean ± SD), DIM 51 ± 23, EBI 195 ± 24 and concentrate
consumed 138 ± 88; JEX cows: parity 2.8 ± 1.2, DIM 58 ± 17, EBI 189 ± 27 and
concentrate consumed 154 ± 64; and NRX cows: parity 2.8 ± 1.4, DIM 53 ± 19, EBI
189 ± 30 and concentrate consumed 154 ± 74. After calving, all cows were allowed full-
time access to pasture and were offered 3 kg concentrate/cow per day. All cows were
calved a minimum of 10 days prior to trial start, were familiar to the farm layout and
were well conditioned to milking and trafficking in the pasture-based AM system. The
experiment consisted of a seven-day adjustment period, a seven-day control period and
a 17 week data collection period. Cows were milked using a Fullwood Merlin 525 AM
unit (Fullwood Ltd, Ellesmere, United Kingdom). Given the overall high ratio of
cows:AM unit (80:1), all cows (including non-trial cows) were allowed a milking
permission of two times per day (minimum milking interval of 12-h) using the Crystal
Software (Crystal 0.44, Fullwood Fusion, Willem Alexanderweg 83, 3945 CH Cothen,
The Netherlands). Therefore, if a cow trafficked to the milking yard within 12-h of her
previous milking event she was denied access to the robot by a pre-selection drafting
gate. The cow was then directed to a post-selection gate where she was sent back to
pasture. All cows (including non-trial cows) were offered 0.5 kg of concentrate/day in the robot during the experimental period. Mean concentrate chemical composition was crude protein (CP) 163 g/kg of dry matter (DM); Crude Fibre 136 g/kg of DM; Ash 54 g/kg of DM; and neutral detergent fibre (NDF) 351 g/kg of DM.

6.3.2 Grazing management

Breed groups grazed as one herd of 80 cows (50 trial cows and 30 non-trial cows), without any physical separation. The experimental grazing area consisted of 25.2 ha divided evenly into three grazing blocks (A, B and C), with 15 individual paddocks in each grazing section separated by permanent fences. Cows were allowed access to each grazing section for 8 hours; block A from 0000 h – 0800 h, block B from 0800 h – 1600 h and block C from 1600 h – 0000 h. Once access to a grazing section had closed no further cows were allowed into that section; however, cows that were already present in that grazing section were allowed to remain there until leaving that section voluntarily. Cows who did not leave the paddock voluntarily were subsequently fetched prior to the opening of the next grazing allocation. The farm was walked weekly to assess farm pasture cover through visual estimation. Paddocks that were deemed to have a pasture cover greater than target were removed from the grazing rotation. Cows were strip-grazed within each paddock, with cows receiving a new strip in each section over each 24 hour period. The size of the area allocated to the herd was determined by calculating the pre-grazing herbage mass. The pre-grazing herbage mass (>4 cm) was determined twice weekly by cutting two strips of grass per paddock (1.2 m × 10 m) using an Etesia mower (Etesia UK Ltd., Warwick, UK). Ten measurements of compressed sward height were taken pre- and post-cutting using a rising plate meter (diameter 355 mm; Jenquip, Feilding, New Zealand). All mown grass from each cut was weighed and then a sample
was collected. A subsample of 0.1 kg was dried at 90°C for 16 hours for DM estimation. Pre- and post-grazing sward height was assessed daily using a Jenquip rising plate meter. Pre- and post-grazing sward heights were measured by taking 30 measurements/grass allocation per day.

6.3.3 Chemical analysis

A composite sample of grass was formed from the two strips of grass cut in each paddock prior to grazing. These samples were frozen at -20°C and at the end of each grazing rotation the samples were bulked by bowl chopping. Samples were subsequently freeze dried for 48 hours, milled though a 1mm sieve and stored for chemical analysis. They were subsequently analysed for DM, ash, acid detergent fibre (ADF), neutral detergent fibre (NDF; ANKOM™ technology, Macedon, NY, USA; (Van Soest et al., 1991)), crude protein (CP; Leco FP-428; Leco Australia Pty Ltd., Baulkham Hills, New South Wales, Australia) and organic matter digestibility (OMD; Fibertec™ Systems, Foss, Ballymount, Dublin 12, Ireland; (Morgan et al., 1989)). The concentrate offered was sampled each week and analysed using near infrared reflectance spectroscopy (NIRS; Foss-NIR System DK, Hillerød, Denmark) for CP, NDF, ash and crude fibre. Results of the grass chemical analyse for the grazed pasture are outlined in Table 6.1.
Table 6.1 Grazing characteristics and grass quality combined for each of the three grazing sections

<table>
<thead>
<tr>
<th></th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-grazing herbage mass &gt;4 cm (kg DM/ha)</td>
<td>1646</td>
</tr>
<tr>
<td>Pre-grazing sward height (cm)</td>
<td>11.7</td>
</tr>
<tr>
<td>DHA (kg DM/cow)</td>
<td>20.9</td>
</tr>
<tr>
<td>Post-grazing sward height (cm)</td>
<td>5.6</td>
</tr>
<tr>
<td>CP (g/kg DM)</td>
<td>196</td>
</tr>
<tr>
<td>ADF (g/kg DM)</td>
<td>266</td>
</tr>
<tr>
<td>NDF (g/kg DM)</td>
<td>405</td>
</tr>
<tr>
<td>OMD (g/kg DM)</td>
<td>828</td>
</tr>
<tr>
<td>Ash (g/kg DM)</td>
<td>130</td>
</tr>
</tbody>
</table>

6.3.4 Data description

Cows were fitted with a leg mounted radio transponder identification device (Afitag, Afimilk, Kibbutz Afikim, 1514800, Israel) that allowed automatic identification at the pre- and post-selection gates and in the milking unit. Thus, data from both the selection gates and the AM unit were recorded electronically. Data recorded by the AM system included cow number, milk yield/milking and per day (kg), number of milkings/day, the daily distribution of milkings, milking interval (hours), milking duration (minutes/cow), average milk flow rate (kg/minute), average dead time/quarter (seconds) and concentrate consumed/cow (kg/cow). At the conclusion of a milking event, that milking event was assigned one of three possible outcomes; successful, yield carry over (YCO) or failure, according to the actual yield of milk produced relative to the expected yield. A milking was deemed successful when >80% of the expected yield was harvested, a YCO was defined as when >20% and <80% of expected yield was harvested, while a failed milking occurred when <20% of expected yield was harvested. After a failed milking, the cow was returned to the milking yard for another attempt at milking. A YCO milking also resulted in an earlier admission (than permitted by the milking
permission setting) of that cow to the milking robot for the subsequent milking, with the timing of re-entry determined by the proportion of milk harvested in the previous milking. All data concerning milking parameters excluded failed milkings since these cows were automatically returned to the pre-milking waiting yard for another milking. The recording of the passing of each individual cow at the selection gates by Logview software (Fullwood Ltd, Ellesmere, United Kingdom) allowed for the calculation of cow traffic variables. These included return time (time, in hours, elapsed from when a cow exited the post- selection gate until she returned to the pre-selection gate) and wait time (time, in hours, elapsed from when a cow entered the pre-milking yard until she entered into the AM unit). The variable return time, represented the average of return times associated with individual visits to the milking yard, whereas the variable wait time represented the average of wait times for individual visits. Wait times were also summed for each 24 hour period to give a daily wait time value. Activity minutes were measured using the leg mounted radio transponder which also acted as a pedometer. The cows were fetched from pasture as one herd on three occasions during the experiment to allow for annual vaccination and implementation of herd health strategies. Data from each of these days and the subsequent 48 hours after treatment were removed from the dataset to allow the cows to re-establish a voluntary routine. Cows had their bodyweight recorded on each of the three occasions using a portable weighing scales and the Winweigh software package (Tru-Test Ltd., Auckland, New Zealand).

6.3.5 Statistical analysis

Data were statistically analysed using least squares means ANOVA using mixed procedure analysis (PROC MIXED) in SAS v9.3 (SAS Institute Inc., Cary, NC, USA). Cow was included as the random effect and therefore weekly measurement was treated
as the repeated measure. Data from the control week was included as the covariate for each dependent variable. Models for variables such as milking frequency, milking interval, milk yield/milking and per day, milking duration/milking and per day, milk flow rate, average quarter dead time, activity/day and return time/visit included the effects for breed, pre-experimental concentrate consumption level, parity, DIM and interactions, while models for wait time/visit and per day also included cow bodyweight to account for the effect that any variation in bodyweight between the breeds may have on waiting time. The covariance structure of models were tested and the selection among autoregressive (1), heterogeneous autoregressive (1), compound symmetry, heterogeneous compound symmetry and unstructured covariance structures were determined based on the lowest Akaike’s Information Criterion and Bayesian Information Criterion (Littell et al., 2006). The Kenward-Rogers method was used for the calculation of degrees of freedom for all mixed models. Significance was set at 5% ($P < 0.05$), with non-significant effects removed from the models by backward elimination. Significance was examined by post hoc analysis of means using a Tukey-Kramer test. The milking event outcome proportions were pooled by treatment and analysed using the logistics procedure (PROC LOGISTIC) of SAS. The daily distribution of milking events were analysed using frequency procedure (PROC FREQ) of SAS. Significance for $\chi^2$ test were used to test between breed groups in relative frequency of milkings at any particular hour. Where significance was determined by the omnibus test, a multinomial logistics regression was performed using the logistics procedure in SAS, to examine the relationships between the breeds.
6.4 Results

6.4.1 Milking frequency, interval and outcome and milk production

Milking parameters such as milking frequency, milking interval and milking outcome are outlined in Table 6.2. While HF and NRX had a numerical greater milking frequency and shorter milking intervals than JEX, there was no significant effect of breed on either of these parameters. When the milking event statuses of each breed was analysed as a proportion of the total milking events for that breed, significant differences ($P < 0.001$) were observed for the proportion of successful milking events, with the NRX cows recording a significantly greater proportion, followed by the HF and JEX. Despite this, there was no significant difference between breeds for YCO milkings. However, the differences in the proportion of successful milking events impacted on the number of failed milking events, with a significantly greater proportion of the JEX milking events ($P < 0.001$) recorded as failed milking events (6.1%). This is in comparison to NRX and HF breeds which had the lowest (0.9%) and intermediate (2.8%) proportion of failed milking events, respectively, with these breeds also differing significantly ($P < 0.001$). Milk production results are also shown in Table 6.2. Numerical differences existed between the breeds for milk yield/day and milk yield/milking, with HF yielding more milk/day and per milking, respectively, than the JEX cows. While the overall differences in milk yield between the breeds were not significant, the difference between HF and JEX approached significance.
Table 6.2 The effect of breed on milking frequency, milking interval, milk yield and milking event outcome

<table>
<thead>
<tr>
<th>Breed</th>
<th>HF(^1)</th>
<th>NRX(^2)</th>
<th>JEX(^3)</th>
<th>SEM(^4)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily milking frequency/cow</td>
<td>1.4</td>
<td>1.4</td>
<td>1.3</td>
<td>0.03</td>
<td>0.72</td>
</tr>
<tr>
<td>Milking interval/cow (hours)</td>
<td>16.1</td>
<td>16.2</td>
<td>16.4</td>
<td>0.51</td>
<td>0.94</td>
</tr>
<tr>
<td>% successful milking events</td>
<td>90.0(^a)</td>
<td>91.8(^b)</td>
<td>86.1(^c)</td>
<td>2.3</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>% YCO(^5) milking events</td>
<td>7.2</td>
<td>7.3</td>
<td>7.8</td>
<td>1.4</td>
<td>0.68</td>
</tr>
<tr>
<td>% failed milking events</td>
<td>2.8(^a)</td>
<td>0.9(^b)</td>
<td>6.1(^c)</td>
<td>0.9</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Milk yield/day (kg/cow)</td>
<td>18.7</td>
<td>17.8</td>
<td>17.1</td>
<td>0.70</td>
<td>0.32</td>
</tr>
<tr>
<td>Milk yield/milking (kg/cow)</td>
<td>13.9</td>
<td>13.2</td>
<td>12.7</td>
<td>0.50</td>
<td>0.19</td>
</tr>
</tbody>
</table>

\(^1\)HF = Holstein-Friesian  
\(^2\)NRX = Norwegian Red x Holstein-Friesian  
\(^3\)JEX = Jersey x Holstein Friesian  
\(^4\)SEM = Standard error of the mean  
\(^5\)YCO = Yield carry over  
\(^a\(^c\)Means within a row with different superscripts differ (P <0.05)

6.4.2 Cow traffic and activity

The effect of breed on cow traffic and activity data is outlined in Table 3. There was a significant difference in return time/visit between the breeds (P <0.05), with NRX cows returning from pasture to the milking yard 42 minutes sooner than the JEX cows. There was also a significant difference (P <0.05) between the breeds for wait time/visit and per day. NRX cows had a significantly shorter waiting time/visit and per day in the pre-milking yard of 0.9 and 1.3h, respectively, compared with the HF cows of 1.3, 1.7h and JEX cows of 1.5 and 1.9h, respectively. A significant difference (P <0.05) was also observed between breeds for daily activity measurements. JEX cows had significantly greater activity levels than HF cows, with the former recording 84 minutes more activity daily.
Table 6.3 Effect of breed on return time, wait time and activity in a pasture-based automatic milking system

<table>
<thead>
<tr>
<th>Breed</th>
<th>Return time/visit (hours/cow)</th>
<th>Wait time/visit (hours/cow)</th>
<th>Wait time/day (hours/cow)</th>
<th>Activity/day (minutes/cow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF&lt;sup&gt;1&lt;/sup&gt;</td>
<td>7.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>642&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>NRX&lt;sup&gt;2&lt;/sup&gt;</td>
<td>7.0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.9&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>666&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>JEX&lt;sup&gt;3&lt;/sup&gt;</td>
<td>7.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>726&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>SEM&lt;sup&gt;4&lt;/sup&gt;</td>
<td>0.33</td>
<td>0.14</td>
<td>0.14</td>
<td>21.6</td>
</tr>
<tr>
<td>P-value</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>

<sup>1</sup>HF = Holstein-Friesian
<sup>2</sup>NRX = Norwegian Red x Holstein-Friesian
<sup>3</sup>JEX = Jersey x Holstein Friesian
<sup>4</sup>SEM = Standard error of the mean
<sup>a, b</sup>Means within a row with different superscripts differ (P <0.05)

6.4.3 Milking distribution

Figure 6.1(a) shows the overall pattern and distribution of milking events of the cows being examined in the experiment, while the effect of breed on the hourly distribution of milking events is outlined in Figure 6.1(b). There was a significant difference in the proportion of milking events in at least one pairwise comparison between the breeds at 12 out of the 24 time points examined. All three breeds differed significantly (P <0.001) at two of those time points, namely, 7 and 8 with JEX having the greatest proportion of milkings at both time points (51 and 48%, respectively), followed by NRX (34 and 32%, respectively) with HF having the lowest proportion of the milking events (16 and 20%, respectively). Both HF and NRX had significantly greater (P <0.001) proportions of milking events than JEX at time points 0, 1, 12 (P <0.01), 17 and 18. Conversely, JEX had significantly more milkings than NRX and HF at time point 6 (P <0.001). Additionally, JEX had significantly more milkings than NRX and HF at time points 4 (P <0.05) and 21 (P <0.05), respectively, and significantly less milkings than NRX at time point 16 (P <0.01).
Figure 6.1 (a) The combined total number of milkings for all cow breeds, represented as an hourly proportion of the total. The time below each bar represents the hour that the milking occurred (i.e. bar 10 represents the milkings that occurred between 1000 h - 1100 h).

(b) The effect of cow breed (HF: Holstein Friesian; JEX: Jersey x Holstein Friesian; NRX: Norwegian Red x Holstein Friesian) on the average hourly distribution of milkings (milkings/breed as a percentage of total milkings at each time point). The time below each bar represents the hour that the milkings occurred (i.e. bar 10 represents the milkings that occurred between 1000 h - 1100 h). Hours with significantly different throughput between breeds ($P < 0.05$) are identified accordingly (*). The vertical bar represents the average standard error of the difference.
6.4.4 Milking characteristics

Results of the milking characteristics such as milking duration/milking and per day, milking speed and average dead time/quarter are presented in Table 6.4. There was no significant effect of breed on milking duration/milking and per day and milking flow rate. Despite having a numerically lower milk yield, the JEX had the longest milking duration/milking and per day, with the HF having intermediate levels and NRX having the shortest milking duration. This may be explained by the slower milking speed of 1.5 kg/min for JEX compared with 1.7 kg/min for HF and NRX. Although not significant with \( P = 0.10 \), this 10% reduction in milk flow rate was approaching significance.

While the aforementioned milking characteristics were not significantly different between breeds, there was a significant effect \( P < 0.05 \) of breed for average dead time/quarter. The JEX cows had 37% less dead time, that is time until milk let-down, than HF cows, who had the longest dead time of 28.5 seconds.

Table 6.4 Effect of breed on milking characteristics in a pasture-based automatic milking system

<table>
<thead>
<tr>
<th>Breed</th>
<th>HF(^1)</th>
<th>NRX(^2)</th>
<th>JEX(^3)</th>
<th>SEM</th>
<th>( P)-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milking duration/milking (minutes)</td>
<td>8.3</td>
<td>8.1</td>
<td>8.6</td>
<td>0.19</td>
<td>0.21</td>
</tr>
<tr>
<td>Milking duration/day (minutes/cow)</td>
<td>11.4</td>
<td>10.9</td>
<td>11.5</td>
<td>0.32</td>
<td>0.46</td>
</tr>
<tr>
<td>Average milk flow rate (kg/minute)</td>
<td>1.69</td>
<td>1.71</td>
<td>1.53</td>
<td>0.060</td>
<td>0.10</td>
</tr>
<tr>
<td>Dead time/quarter (seconds)</td>
<td>28.5(^a)</td>
<td>27.7(^a)</td>
<td>17.6(^b)</td>
<td>2.18</td>
<td>(&lt;0.01)</td>
</tr>
</tbody>
</table>

\(^1\)HF = Holstein-Friesian
\(^2\)NRX = Norwegian Red x Holstein-Friesian
\(^3\)JEX = Jersey x Holstein Friesian
\(^a\)\(\)Means within a row with different superscripts differ \( P < 0.05 \)
6.5 Discussion

While Nieman et al. (2015) previously reported the performance of different strains of the HF breed in a pasture-based AM system, as far as we are aware, the current experiment represents the first analysis conducted using the controlled settings of a research herd to compare the effect of dairy cow breed on milk production, milking characteristics and cow traffic parameters in a pasture-based AM system. While, Clark et al. (2014) examined the cow traffic performance of HF and Illawarra breeds, that study was conducted retrospectively from research herd data, had varying numbers of cows within each breed. Furthermore, the current component study not only encompasses breeds such as the HF, which are common to global pasture-based systems, but also crossbreds which have been identified as being particularly suited to the efficient conversion of pasture to high value milk, such as the JEX (Goddard and Grainger, 2004, Prendiville et al., 2009, Coffey et al., 2016) and NRX (Begley, 2008, Walsh et al., 2008, Begley et al., 2009a).

6.5.1 Milk production, milking frequency, interval and outcome

The results of the current experiment with regard to milk yield are largely in agreement with those from previous experiments. Walsh et al. (2008) and Begley et al. (2009b) compared purebred Norwegian Red and NRX, respectively, to the HF. Both studies indicated that the respective breeds had similar yields of milk volume to HF cows. When examining the performance of the JEX cows in the current experiment, the trends were similar to those observed in previous studies (Auldist et al., 2007, Prendiville et al., 2011, Vance et al., 2013), with JEX cows having less milk volume than HF.
Milking frequency did not differ significantly between breeds. However, the JEX cows did record a significantly lower and greater proportion of successful and failed milking events, respectively, compared to the other breeds. Further examination of the raw data showed that the JEX cows had a far greater variation in milking interval than the HF and NRX breeds. They had a greater proportion of milkings with intervals <12 hours (due to failed and YCO milkings allowing cows access to the AM unit sooner than normally permitted under the selected milking permission settings) and a greater proportion of milkings with intervals >20 hours. This greater variation in milking interval creates the potential for large changes in udder shape between milkings, resulting in greater difficulty achieving successful cup attachment (Jago et al., 2007). While the HF breed were intermediate between the JEX and NRX, they also achieved significantly lower successful and significantly greater failed milkings compared to the NRX cows. However, the differences recorded (2%) were not as pronounced as those between the JEX and NRX (5%); thus, HF performance was more comparable to NRX than JEX.

6.5.2 Cow traffic and milking distribution

While the cows in the current experiment were not ranked based on social dominance, as was the case for Jago et al. (2003), that study provides some possible explanations for the trends in cow traffic parameters observed in the current experiment. The NRX cows had the shortest return time, followed by the HF, while the JEX cows had the longest. Jago et al. (2003) observed that when cows have negative experiences on roadways or in milking waiting yards, including encounters with cows of higher social rank within the herd, that this can reduce the motivation of those cows to move from pasture to the AM unit. An experience that could be considered negative in the current experiment
may be the significantly longer pre-milking yard waiting time, both per visit and per day for the HF and JEX cows than the NRX cows, thus, resulting in the longer return times than the NRX cows. Longer pre-milking yard waiting times could also have an effect on grazing time with cows waiting the longest, grazing the longest (Jago et al., 2003); however this was not measured in the current experiment. Incidentally, Prendiville et al. (2010a) demonstrated that JEX cows were more intensive grazers than both their parent breeds in a conventional milking (CM) system, grazing for 20 minutes longer, with a higher bite rate and grass dry matter intake. However, the grazing dynamic may be very different in an AM system, as cows enter pasture at varying stages of pasture depletion; thus, cows which enter a pasture allocation last, have to graze for longer to achieve the same level of nutritive intake as those that entered the pasture allocation at an early stage (Clark, 2013, John et al., 2015).

Examination of the distribution of milking events across the day indicated a significantly greater proportion of both HF and NRX cows milking immediately following the opening of two out of the three fresh allocations of pasture. This indicated that more cows from those respective breeds entered the fresh pasture allocation before a substantial depletion of it would have taken place. Interestingly, a substantially greater proportion of JEX cows were milked between time points three and eight and considering that the fresh pasture was made available in block A at midnight, milking between these times may indicate the entry of these cows into grazing block A at a time when there was considerably less pasture available than if they were milked earlier. Ketelaar-de Lauwere et al. (1996) reported lower social ranking cows visited the AM unit more frequently during the midnight to 6am period, while Jago et al. (2003) found that more milkings of lowering ranking cows occurred during the late evening period.
Based on the findings of those studies, and the distribution of milking events among the breeds in the current experiment, it could be hypothesised that HF and NRX breeds were among the more highly ranked cows in the study, while the JEX cows represented some of the more lowly ranked cows. However, the study of Ketelaar-de Lauwere et al. (1996) was based on an indoor AM system and caution is recommended when drawing comparisons with pasture-based systems. The significantly reduced number of milkings for JEX cows immediately after the opening of fresh pasture at time points 0, 1 and 17 would indicate that if those cows did traffic to the milking yard anticipating the allocation of fresh pasture at those time points, they were not successful in accessing the AM unit in the presence of the HF and NRX cows, as there may have been a behavioural limitation on the behalf of the JEX cows (Jago et al., 2003). Conversely, at the allocation of fresh pasture at time point 8, the JEX cows had a significantly greater proportion of milkings, both at that time point and at the previous time point (time point seven) than the other two breeds examined. The reasons for this are unclear, and it may be a consequence of the JEX remaining present in grazing block C for an extended duration and, as a result only trafficking from pasture to the milking unit upon sunrise. Additionally, the diurnal grazing pattern of dairy cows (Gregorini, 2012) may have resulted in reduced grazing time for the cows in block A compared with the other blocks, meaning that upon the opening of fresh pasture in block B at time point 8, there was potentially a substantial amount of pasture remaining in the previous allocation, which may have discouraged the cows who trafficked to block A from leaving. However, this remains conjecture, as cows were not either visually or electronically monitored for location or time of entering or exiting pasture.
6.5.3 Milking characteristics

To date, there has been little research carried out on the effect of different breeds on milking characteristics such as milking duration, average milk flow and dead time. Both Arave et al. (1987) and Prendiville et al. (2010b) examined the difference in milking duration/day between HF, Jersey and JEX in a twice daily milking pasture-based CM system over the entire lactation. In line with the current experiment, no differences were found between the HF and JEX for milking duration. Likewise, Walsh et al. (2007) compared the milking characteristics of the HF and purebred Norwegian Red and found them similar in terms of milking duration and milk flow rate. However, it was noteworthy, that while there was no breed effect for average milk flow in the current experiment, the difference is approaching significance \( (P = 0.10) \). Dead time/quarter, or the period to milk let-down, was significantly shorter in the JEX cows than both the HF and NRX cows. This is likely a direct consequence of selection against cows with a requirement for udder stimulation to trigger milk let-down within the Jersey breed (Phillips, 1986), as udder preparation is not regularly practiced as part of the milking routine in New Zealand where there are a large population of Jersey cows (Jago et al., 2006a). Phillips (1986) also demonstrated that when pre-milking stimulation was applied, both Jersey and JEX cows showed a greater response than the HF breed.

6.5.4 Additional considerations

As outlined earlier, the current experiment was a component study during the mid-lactation period of a seasonal calving herd, focusing predominantly on the milking and cow traffic performance of the respective breeds. Thus, it is important to consider these results in the context of a whole farm system, where key performance indicators not considered in this experiment such as milk solids production, fertility, survivability and
efficient conversion of feed to high value milk are vital aspects of a profitable milk production system. Given the reduced profitability of AM compared with CM in low cost pasture-based systems (Jago et al., 2006b, Shortall et al., 2016), increasing grass intake by the cow and subsequent milk solids harvested per robot will be of particular importance with an AM system. Woolford et al. (2004) suggested that this should be achieved with up to 100 cows/robot. However, in a seasonal calving system the robot will be the limiting factor in peak lactation, with potential for extended milking intervals. However, Hogeveen et al. (2001) and Lyons et al. (2013c) have both highlighted that milk production remains steady for up to a 16 hour milking interval, but declines subsequently. Thus, a robust cow capable of sustaining periods of long milking intervals is required for AM in a pasture-based system. Similarly, for optimisation of the AM system it is important to have an even distribution of milkings throughout the day. Based on the evidence from the current experiment, this may be best achieved by a mixed breed herd rather than a single breed herd.
6.6 Conclusion

The objective of this study was to examine the effect of cow breed in a mixed breed AM dairy herd on milk production, cow traffic and milking characteristics. While breeds did not differ significantly for milking frequencies, differences existed within the cow traffic parameters measured. NRX cows had the shortest return time and pre-milking yard waiting time while the JEX cows had greater activity levels. The distribution of milking events showed that the HF and NRX cows were visiting the yard in anticipation of the allocation of fresh pasture. These data indicated that the NRX cows trafficked most efficiently through the system and were a more dominant breed of cow. However, the performance of the breeds should be analysed in the context of the whole AM farm system over an entire lactation, both as a mixed and single breed herds, taking into consideration the range of variables that contribute to a profitable farm system.
Chapter 7: Summary, general discussion and future research
7.1 Summary

7.1.1 Thesis objectives

The overall objective of this thesis was twofold:

i) To establish the environmental, social and economic sustainability of farming with automatic milking (AM)

ii) To establish the knowledge gaps relating to cow traffic and once identified, determine their effects within the context of a pasture-based AM system

7.1.2 Chapter 2: Literature review

Chapter 2 provides a comprehensive review of the literature relating to the thesis objectives as outlined above.

The main findings were:

- The Irish dairy industry is undergoing a substantial period of growth with the average herd size expected to increase from 76 cows in 2016 to 104 cows in 2025
- Difficulties attracting suitably skilled labour is one of the biggest challenges facing the sector, with an estimated 6,000 labour units required on Irish dairy farms by 2025
The integration of AM with pasture-based production systems represents a feasible alternative to conventional milking (CM) which may help alleviate some of the labour shortages facing the industry at farm level.

While changes in labour associated with the adoption of AM have been identified for confinement production systems, there is a gap in the knowledge in relation to the impact AM adoption may have in a pasture-based production systems.

The method of data collection to quantify the change in labour associated with AM adoption may also have an impact on the findings, with an on-going audit process to capture any variation throughout a production season identified as the preferred method of data collection, rather than a once-off survey.

Studies which have quantified the electricity consumption of an AM unit have occurred over short time periods, therefore capturing very little variation which may occur from day to day. Thus, this review highlighted the importance of developing an understanding of total AM farm electricity and water consumption, encompassing an entire production season, as it provides a more accurate representation of the key consumers.

To date both the daily and seasonal trends in electricity and water consumption remain undocumented for an AM system.

Given the popularity of AM adoption in confinement production systems and the relatively recent adoption of AM into pasture-based systems, it not unexpected that studies examining the economic outcome of AM adoption are focused primarily on indoor production systems. Thus, the need exists to examine how AM adoption affects the economic sustainability of a dairy farm within the context of a seasonal calving pasture-based system, where calving and milk
production patterns differ substantially from those found in a typical confinement system

• Taking cognisance of the increasing array of sensors and technological components available within CM parlours it is important to draw comparison not alone between AM and standard CM parlours, but also between AM and CM parlours of comparable technological standards

• Substantial knowledge gaps in relation to cow traffic performance and how cows can be influenced in the context of pasture-based AM systems were identified

• The studies reviewed identified that late lactation cows are less motivated to traffic voluntarily for milking and more likely to experience extended milking intervals. This is of particular importance to seasonal production systems

• From the studies reviewed, feed was identified as the primary incentive for cows to traffic to the milking yard, thus any examination of ways to improve late lactation cow traffic should establish how feed impacts on cow traffic performance during this period

• From conducting this review, it has also become clear that the findings relating to the performances of various breeds in AM systems are scant. This is of particular importance to AM pasture-based systems, as some breeds have been identified as being more suited to the seasonal grazing system than others. Furthermore, a knowledge gap has been identified with regard to the complementarity of differing breeds in the context of a mixed breed herd
7.1.3 Chapter 3: Daily and seasonal trends of electricity and water use on pasture-based automatic milking dairy farms

The objective of this chapter was to establish the daily and seasonal trends of electricity and water consumption on AM dairy farms in pasture-based systems over a year long period, while also identifying the main contributing process to total consumption. Dairy farm processes and equipment that were metered for electrical consumption included milk cooling components, air compressors, AM unit(s), auxiliary water heaters, water pumps, and “other”, such as lights, sockets, automatic manure scrapers, etc. On-farm direct water consuming processes that were metered included AM unit(s), auxiliary water heaters, tubular coolers, wash-down water pumps, livestock drinking water supply, and miscellaneous water taps. Milk production data were obtained from the companies to which the milk was supplied, cow numbers were obtained from a monthly questionnaire, while level of concentrate offered to the cows, number of milkings/AM unit per day and number of cows milked/AM unit per day were obtained from the milking system software package.

The main findings were:

- Total farm electricity consumption and costs were 62.6 Wh/L of milk produced and 0.91c/L, respectively
- Milking (vacuum and milk pumping, within AM unit water heating) had the largest electrical consumption at 33%, followed by the air compressor (26%), milk cooling (18%), auxiliary water heating (8%), water pumping (4%) and other processes (11%)
• The average electricity consumption was 20.5 kWh per day, while the average cost of operating an AM unit was €2.76 per day.

• A single unit configurations used more electricity (gross kWh)/AM unit on an annual and daily basis than the double unit configurations.

• Both configurations used a similar quantity of electricity per milking indicating that the differences in electricity consumption per AM unit are as a result of differing cow stocking densities/AM unit.

• As the number of milkings/AM unit increased, the electricity consumption per liter of milk decreased.

• The trends in seasonal electricity consumption followed the seasonal milk production curve.

• The pattern of daily electricity consumption was similar across the lactation periods, with peak consumption occurring at 0100 h, 0800 h and between 1300 and 1600 h.

• Total water consumption was 3.7 L of water per L of milk produced.

• Water consumed in the milking shed represented 42% of total farm consumption, with livestock/miscellaneous constituting the remainder.

• Pre-cooling of milk in the tube-cooler had the largest requirement for water in the milking shed, followed by milking (AM units), the wash-down process and auxiliary water heating.

• Water from the tube cooler was made available to other processes for reuse, with the livestock/miscellaneous process having availed of the greatest proportion of it (55%), followed by the wash-down process (29%) and the AM units (16%).

• When analysed as a proportion of the total consumption for each of the three components, recycled water comprised 100% of the water used for the wash-down.
process, 37% of the water for the AM units and 23% of the water for livestock/miscellaneous

- The average AM/unit consumed 4.3 L of water/milking or 445 L/day
- Seasonal water trends mirrored the seasonal milk production curve
- These findings have the potential to assist in developing future strategies that may improve the competitiveness of the AM system

7.1.4 Chapter 4: Investment appraisal of automatic milking and conventional milking technologies in a pasture-based dairy system

The objective of this chapter was to identify the profitability of AM relative to CM herringbone parlours with two different levels of technology, over a 10-year period across two farm sizes, in a pasture-based system. The scenarios which were evaluated were

(i) A medium farm (MF) milking 70 cows twice daily, with one AM unit (AMS-SU), a 12 unit CM medium specification (12MS) parlour and a 12 unit CM high specification (12HS) parlour

(ii) A large farm (LF) milking 140 cows twice daily with two AM units (AMS-DU), a 20 unit CM MS (20MS) parlour and a 20 unit CM HS (20HS) parlour

A stochastic whole-farm budgetary simulation model combined capital investment costs and annual labour and maintenance costs for each investment scenario, with each scenario evaluated using multiple financial metrics. The capital required for each investment was financed from borrowings at an interest of 5% and repaid over 10 year,
while milking equipment and building infrastructure were depreciated over 10 and 20 year, respectively.

The main findings were:

- Labour demand was reduced by 36% with the adoption of an AM system
- Reduced labour with AM can be attributed to significantly less time \( P < 0.001 \) spent at the daily milking process (0.7 vs 3 h/day for AM and CM, respectively)
- AM farmers started work significantly later (7:55am; \( P < 0.05 \)) in the day than CM farmers (07:05am); however end times were similar
- Labour costs as a proportion of total costs were 12%, 20% and 19% of AM, CM MS and CM HS, respectively
- At the MF size the greatest total discounted net profit was recorded in the 12MS system, followed by the AMS-SU, with the least profit recorded in the 12HS
- At the LF size the greatest total discounted net profit was recorded by the 20MS, followed by the 20HS. The AMS-DU recorded a marginally lower profit than the 20HS
- Despite higher labour costs, the lower depreciation, interest and maintenance costs associated with MS parlours led to the greatest profitability
- Although increasing the value of labour reduced the difference in the profitability between CM and AM systems, the trends observed previously were maintained with MS, AM and HS recording the greatest, intermediate and least profit, respectively
- This analysis suggested that maximising profitability should not be the reason for investing in AM technologies
The objective of this chapter was to establish the effect of two differing levels of concentrate supplementation, in the early and late lactation periods, on milk production and cow traffic parameters in a seasonal calving pasture-based AM system. Forty spring-calving dairy cows were randomly assigned to one of two possible flat rate concentrate feeding treatments:

(i) a low concentrate (LC) supplementation level where cows were offered 2.3 and 0.5 kg/cow per day in early and late lactation, respectively

(ii) a high concentrate (HC) supplementation level where cows were offered 4.4 and 2.7 kg/cow per day in early and late lactation, respectively

Variables measured included milking frequency, -interval, -outcome and -characteristics, milk yield/visit and per day, wait time/visit and per day, return time/visit and the distribution of gate passes. As the herd was seasonal (spring) calving, the experimental periods could not run concurrently and as a result no statistical comparison between the periods was conducted.

The main findings were:

- Early lactation
  - There was no significant effect of treatment on any of the milk production, milking characteristics or cow traffic variables
Treatment had a significant ($P < 0.01$) effect on the number of successful and yield carry over (YCO) milkings with the HC treatment recording a lower and greater proportion than LC, respectively.

Treatment significantly affected the distribution of gate passes, with the HC cows recording significantly more gate passes in the hours preceding the gate time change such as hours 7 ($P < 0.01$), 15 ($P < 0.05$), 20, 21 ($P < 0.001$) and 22 ($P < 0.05$).

The LC treatment recorded significantly more gate passes in the hours succeeding the gate time change, such as time points 2 ($P < 0.01$) and 10 ($P < 0.05$).

- Late lactation

  - The HC treatment had a greater milk yield ($P < 0.01$), milking duration and activity/day ($P < 0.05$).
  - Significantly shorter milking interval ($P < 0.05$) and return time/visit ($P < 0.01$) were also achieved by the HC treatment.
  - Treatment had a significant effect on the number of successful and YCO milkings with the LC treatment recording a lower ($P < 0.01$) and greater ($P < 0.05$) proportion than HC, respectively.
  - The distribution of gate passes were similar to the early lactation period, with HC recording a significantly ($P < 0.01$) greater number of gate passes during the early morning period (0300 – 0400 h) when visitations were at their lowest.

Any decision regarding the supplementing with concentrates needs to be examined from an economic perspective, the benefits displayed in late lactation outweigh the cost of the concentrate.
7.1.6 Chapter 6: The effect of dairy cow breed on milk production, cow traffic and milking characteristics in a pasture-based automatic milking system

The objective of this study was to evaluate the performance of three breeds with regard to milk production, cow traffic and milking characteristics in a mixed breed pasture-based AM system. The breeds monitored were the Holstein Friesian (HF), Jersey x HF (JEX) and Norwegian Red x HF (NRX). The experiment was conducted in mid-lactation and variables measured included milking frequency, interval, outcome and characteristics, milk yield/milking and per day, wait time/visit and per day, return time/visit and the daily distribution of milking events.

The main findings were:

- No significant differences were observed between breeds for milking frequency or interval
- Breeds differed significantly \( P < 0.001 \) for the proportion of successful and failed milkings, with the NRX achieving the greatest proportion of successful milkings, intermediate for HF and the lowest proportion for JEX
- The inverse occurred with failed milkings \( P < 0.001 \), with the greatest proportion being recorded by JEX, intermediate by HF and lowest by NRX
- The NRX cows returned to the milking yard significantly \( P < 0.05 \) sooner than the JEX (0.7 hours)
- The NRX breed recorded the shortest \( P < 0.05 \) pre-milking yard waiting time both per visit and per day
- The HF cows recorded the lowest activity level, significantly lower than the JEX cows ($P < 0.05$; 642 vs 726 minutes)
- The JEX cows recorded a dead time that was significantly lower ($P < 0.01$) than both the HF and NRX breeds
- The distribution of milking events between the breeds, with the JEX cows recording less milkings in the hour after the pre-selection gate changes of 0000 h and 1600 h
- JEX also recorded a significantly greater proportion of milkings than the NRX and HF cows during the hours at which the lowest proportion of total milking events were recorded (0400 h – 0600 h)
- AM optimisation may be best achieved by a mixed breed herd rather than a single breed herd

7.2 General Discussion

The Irish dairy industry is undergoing a significant growth phase, with the national herd expected to increase by 260,000 cows by 2025, while dairy farm numbers are estimated to remain static (Teagasc, 2017). This expansion will place substantial strain on existing farm labour sources and may see farmers turn to technology, allowing demand on labour to be eased through the automation of tasks. With the CM milking process accounting for one-third of all labour use on dairy farms, it is not surprising that AM is increasing in popularity. Thus, developing knowledge with regard to the integration of the system into a pasture-based system was paramount to this thesis.
With the automation of the milking process removing the need for the presence of an operator at specific times each day, it is not surprising that the labour audit within the current thesis identified a 36% reduction in labour associated with AM. The reduction in time spent at milking related tasks on the AM farms was not outweighed by the increase in time associated with grass allocation on the AM farms. Given the dependence on feed as the primary motivator for cows to traffic to the milking yard (Prescott et al., 1998), this is an interesting finding and one which highlights the importance placed on correct pasture allocation on AM farms.

However, while labour is one of the reasons for adopting AM, concerns surrounding the profitability of the system are a potential reason for not adopting the technology. When comparing AM with CM parlours of MS, the findings of this thesis back up these concerns. The reduced profitability of AM relative to a MS parlour is as a result of increased costs associated with the system, such as electricity, maintenance, depreciation and interest. However, while the MS parlour performs the basics of milk harvesting, the addition of technology to such a parlour has the potential to provide milking operators with enhanced comfort and reduced fatigue. With dairy farms expanding and labour availability decreasing farmers may look to automating components of the CM process to provide a more structured milking routine. Thus, it was necessary to compare AM to such automated CM parlours of HS. Interestingly, the AM system provides a greater/similar financial return, depending on the herd size. However, when labour costs increase, the AM system provides a far greater return than CM HS at all herd sizes as, despite automation of certain tasks, the presence of a milking operator is still required for cluster attachment. Thus, decision making regarding investment in new milking technology needs to encompass the desired
workload of the individual, the cost and availability of skilled labour and the economic goals of the farm. If the objective of the farm is to reduce labour requirements, the adoption of AM will achieve this.

As mentioned above, electricity costs associated with AM are greater than those of CM systems previously described in the literature, as outlined in Chapter 3. Considering the continuous operational nature of the AM system and the magnitude of electronics associated with the system, this is expected. However despite this, the findings from this thesis indicate that key drivers of electricity consumption associated with AM are the air compressor and water heating within the AM unit. An interesting and unexpected finding was the reduction in total farm water consumption relative to CM farms (Murphy et al., 2014) previously described in the literature. Due to the smaller physical footprint of an AM unit relative to a CM parlour for a similar herd size, a reduced volume of water was required for the washing of the milking area. This allowed recycled water which was retained for the wash-down process to be used for the AM units and livestock drinking water, as it was no longer required for washing. This is an important finding in a global context, particularly in countries where water availability is a key challenge facing the dairy industry.

While the findings of chapters 3 and 4 will assist potential AM adopters with their decision making process, thought should be given to the experimental approach taken within these studies. The use of commercial farms as opposed to a research setting for the quantification of labour, electricity and water consumption provides commercial farmers alike with more relevant findings. This is due to a greater level of available labour and the potential for extended milking processes, as a result of experimental
procedures in a research setting. However, the number of AM commercial farms used in this thesis is low (seven). This may cause a potential limitation, as (i) the greater the number of farms the greater the accuracy of the data and (ii) the lower number of farms may not allow for variation of differing production systems to be accounted for. Although, this number of farms may be small, the total number of farms milking with AM was also small at the time of selection; thus the seven farms may still represent approximately 2 - 3% of AM dairy farms in Ireland at that time.

Voluntary cow traffic is the foundation on which successful AM systems operate and it is the basis for an even and distributed milking pattern. Jago et al. (2006c) identified that late lactation cows are less motivated to traffic voluntarily for milking and more likely to experience extended milking intervals. Given the seasonal nature of the Irish pasture-based production system and the influence of feed on cow traffic, it was necessary to investigate the effect of supplementation levels on cow traffic. The use of concentrate supplement proved successful in reducing milking interval and return time from pasture. Furthermore, there was no effect of supplement level in the early lactation period on factors such as milking duration, indicating that feeding a HC level, should the need arise, would not be detrimental to AM efficiency with a high cow:AM unit ratio. In the evaluation of three breeds in a pasture-based AM system, it is interesting to note the complementary nature of the breeds. This is an important factor to consider with the adoption of AM in a pasture-based system, where the objectives of the system are to achieve high levels of both AM and pasture utilisation. The results from the experiment conducted in this thesis would indicate that a mixed breed herd is best for achieving AM farm optimisation. The NRX cows examined, trafficked through the system most efficiently, with the JEX cows recording the greatest activity levels and
while this led to longer return times from pasture for the JEX cows, it may also be an indication of a more intensive grazing behaviour on the part of this breed. This would in turn help to achieve high levels of pasture utilisation.

While the use of one AM unit and one farm-let in chapters 5 and 6 ensured (i) all treatments were grazing the same pasture, (ii) they were the same distance from the milking yard and (iii) allowed for the different breeds to be examined as a mixed breed herd, it also has several disadvantages. Firstly, having multiple treatments grazing, trafficking and milking together creates the potential for treatments to influence one another; for example it is possible in chapters 5 that the greater motivation of the HC treatment to traffic voluntarily to milk may have influenced the LC treatment and resulted in the LC treatment trafficking from the paddock sooner than they would have if they had their own independent farm-let. This is particularly pertinent to AM, as voluntary cow traffic is one of the most important metrics determining the success of the system. This may also be exasperated by any non-trial cows milking on the AM unit. Furthermore, the use of one farm-let for grazing all treatments as a combined herd reduces the number of key grazing metrics that can be measured; in the context of this thesis namely the rate of pasture substitution when supplementation was offered and the effect of treatment on pasture utilisation and post-sward grazing height. This makes the effect of treatment in an AM pasture-based system less clear. However, due to the large level of resources required to perform a systems study for pasture-based AM with multiple treatments and independent farm-lets for each, the methodology used herein (e.g. one AM unit for multiple treatments) is likely to remain the most cost and resource effective. Nonetheless, when interpreting the results from chapters 5 and 6 it is
necessary to take consideration the potential influence that the treatments may have had on one another.

The research conducted in this thesis represents the first time that AM has been investigated in the context of a seasonal, low-input pasture-based production system. Thus, the findings presented in this thesis represent a benchmark for AM system performance in such a production system and provide both farmers and industry alike with a significant body of information to allow informed decision making regarding the adoption of AM technology.

7.3 Future Research

The findings of this thesis also identify potential areas of future research which may help increase both the suitability of AM to and the sustainability of AM in a seasonal pasture-based production system. Results from the labour audit in chapter 4 indicate a substantial reduction in work load associated with the adoption of AM. While the reasons for AM adoption (reduced labour, greater time flexibility, etc.) have been well documented in previous international research, it is also important to develop an understanding of the circumstances surrounding the adoption of this technology and how satisfied are farmers with their decision post-adoption. This could be achieved through a combination of once off survey to establish information regarding the farming operation (e.g. farmer age, demographic, family circumstances) and a qualitative study to establish if farmer expectations have been fulfilled. Furthermore, production (milking frequency, milk production, milk quality, fertility performance, animal health records, pasture production etc.) and financial data should be obtained from AM farms over
multiple years, encompassing years both prior to and post adoption, to establish if AM adoption led to changes in these parameters. This would also allow farmers considering AM to make a greater assessment of what effect adoption may have on the physical performance of their farm.

Results from Chapter 3 and 4 highlight the need for an increased cow:AM unit ratio. Electricity consumption of the two largest on farm electricity consumers, the AM unit and air compressor, decreased per unit of output (litre of milk) as the number of milkings increased. Furthermore, to improve the economic sustainability of the system it will be necessary to increase the amount of milk harvested/AM unit. While it may be possible to achieve these objectives through increasing the number of milkings/cow, the aim of a low cost pasture-based system is to reduce costs by maximising the proportion of grazed pasture in the diet of the dairy cow and minimising the proportion of purchased supplements. Thus, for pasture-based farmers operating the aforementioned production system, harvesting additional milk through increased cow numbers will be the most suitable strategy. However, as the seasonal nature of the production system examined results in a large proportion of the herd reaching peak milk production together, which in an AM system puts substantial pressure on the milking unit at that period of the year, resulting in the peak milk production period becoming a limiting factor. Thus, future research should focus on milking frequency management and the development of efficient milking strategies to limit the impact of increased cow numbers on milking and cow traffic variables during the peak milk production period. Increasing cow numbers/AM unit may also increase the number of cows within the herd of a lower social rank, making it more difficult for these cows to access resources. Therefore, for a system with a high cow:AM ratio the development of infrastructure,
such as a priority pre-milking yard to facilitate easier access to milking resources for these cows and to reduce impact of cows of a higher social rank, will be imperative to the success of such a highly stocked system. Thus, future research should quantify the impact of such infrastructure on the performance of lower ranking cows.

However, while every effort should be made to maximise the ratio of cows:AM unit, it is likely that it will not be possible to achieve this on many farms, as land may become the limiting resource before the AM unit. Thus, it is also imperative to investigate the impact of treating cows to an individual milking and feeding approach, as a means to maximising AM output where it is not possible to do so through increased cow numbers. In a compressive review of supplementing dairy cows in pasture-based system, Hills et al. (2015) outlined how there is a need to determine responses to individualised feeding strategies in rotational grazing situations, in which pasture allowance is restricted. This is particularly pertinent to AM systems where cows are being asked to graze out up to three pasture allocations per day as opposed to one in a CM system. Thus, it is likely that for some cows in an AM system that pasture will be restricted and that quality of pasture consumed may be of a lower standard, depending on a cows position in the herd’s social hierarchy. Thus, cows lower in the dominance spectrum may benefit from additional supplementary feed, although these cows are likely be impacted upon less where the ratio of cows:AM unit is low. However, it would be necessary to investigate this targeted milking and feeding approach from a whole farm approach to establish if it has any negative consequences on farm kpi’s, such as pasture utilisation or dairy cow reproductive performance, as well as on AM parameters such as cow traffic. Nonetheless, this may serve as an alternative means to maximise
output in a seasonal pasture-based AM system where land is the limiting resource and the ratio of cows:AM unit is approximately 55-70 cows.

Chapter 5 highlighted how the visitation pattern of the herd to the milking yard in a pasture-based AM was concentrated around the availability of fresh pasture, while Chapter 6 outlined how a limited number of milkings occur in the early morning period (0400 – 0600 h), concurring with previous international research (John et al., 2016). Future research should focus on developing strategies to achieve a more distributed visitation and milking pattern. These strategies may involve the availability of an additional pasture allocation, the separation of the herd in two, with each herd trafficking to the milking yard at alternate times or the allocation of fresh pasture during the early morning period (0400 – 0600 h). Increasing AM utilisation during the early morning period would also have a knock on effect of increasing the proportion of electricity consumption during the cheaper night-rate period. While this would be welcome, it should not constitute the sole method of reducing electricity costs. Taking cognisance of the daily electricity consumption profile, it is essential that an investment appraisal is undertaken to ascertain the suitability of differing renewable technologies for adoption in combination with an AM system. This would establish if the electricity consumption reductions and the capital costs associated with such technologies make them a prudent financial investment.
Chapter 8: Bibliography


Prendiville, R., K. M. Pierce, and F. Buckley. 2010b. A comparison between Holstein-Friesian and Jersey dairy cows and their F1 cross with regard to milk yield, somatic cell score, mastitis, and milking characteristics under grazing conditions. J. Dairy Sci. 93:2741-2750.


223


Chapter 9: Publications
9.1 Peer Reviewed Journal Publications


9.2 Conference Publications


9.3 Technical Articles


