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Exploring strategies to enhance farm animal welfare with Digital Livestock Technologies

A Thesis Submitted for the Degree of Doctor of Philosophy

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Declaration of original authorship

Declaration: I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

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Abstract

Digital Livestock Technologies (DLTs) are considered a key solution in responding to animal welfare concerns by facilitating livestock monitoring and management. However, the impacts of DLTs on animal welfare are unclear, and their use raises social and ethical concerns. This study was designed to explore the extent to which DLTs can help end-users enhance animal welfare, and how their uptake can be promoted whilst minimising negative consequences. Two case studies were used to explore the experiences of end-users and other stakeholders involved in trialling DLTs with semi-structured, in-depth interviews (N=31). A survey (N=145) and a workshop were used to complement the findings. Results highlighted the important potential of current DLTs to address most dimensions of animal welfare. However, their ability to promote positive affective states remained limited. Whether these important dimensions will be considered in management decisions may depend on DLTs' ability to act as boundary objects: facilitating stakeholder communication and co-learning, and a re-framing of end-users' values and beliefs. Findings also suggested the importance of considering the challenges of technology implementation. When used in farm assurance schemes, DLTs could help improve the consistency of data collection; increasing consumer trust and fairness between farmers. However, farmers also expressed concerns over data ownership, reliability, and use. Whilst some of these concerns can be identified and addressed during participatory approaches, challenges such as technology failures, lack of communication, or inadequate training, can also create frustration and impact end-users' engagement in these processes. Enhancing animal welfare with DLTs is therefore not straightforward. Greater attention should be paid to the type of DLTs used and their ability to promote learning and changed management practices. The focus should also be on building trusting relationships between stakeholders, and on whether end-users' concerns will be addressed through more efficient collaboration with relevant stakeholders involved in DLT development.

À ma famille.

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CONTENTS

List of acronyms

AI	Artificial Intelligence
AMS	Automated Milking System
AWRN	Animal Welfare Research Network
BCS	Body Condition Score
DLT	Digital Livestock Technology
DSS	Decision Support System
FDM	Five Domains Model
HAI	Humain-Animal Interaction
HAR	Human-Animal Relationship
IQR	Interquartile Range
PLF	Precision Livestock Farming
RFID	Radio Frequency Identification
TRL	Technology Readiness Level
WQ®	Welfare Quality®

CHAPTER 1. Introduction

1.1. Background

In recent years, the role of agricultural digital technologies to address the challenges linked to the ever-growing human population, which is expected to rise above 9 billion people by 2050, has become increasingly evident (Barrett and Rose, 2022). This role is particularly relevant in the livestock sector, as, while the human population has tripled between 1950 and 2022[1], global meat production has quadrupled between 1961 and 2017 (Ritchie, Rosado and Roser, 2017). Nations must therefore develop strategies that address concerns relating to the intensification of livestock farming, including those over sustainability, climate change, and the health and welfare of humans and animals (FAO, 2018). In the UK, the post-Brexit *Animal Health and Welfare Pathway* includes strategies to support the use of new technologies and innovations which have the potential to enhance animal welfare through financial incentives, using 'public funds to deliver public goods' (Defra, 2020, p.46). Farm animal welfare is considered an integral part of sustainability, especially as it resonates among the public which is increasingly concerned over the ways farm animals are protected and kept for food production (Broom, 2010; European Commission, 2016; García Pinillos *et al.*, 2016). As livestock numbers are increasing and employment in agriculture is decreasing globally (FAO, 2018; Defra, 2019; eurostat, 2020), attending to the needs of hundreds to thousands of individual animals per farm is becoming ever more difficult [and likely impossible in modern large-scale fish farming, where millions of individuals can be found on one farm (Føre *et al.*, 2018)]. In 2020, the international news organisation *Reuters* published an article[2] on the China-based company *Muyuan Foods Co., Ltd*, a farm which is expected to house 84,000 sows and piglets at any one time and to produce over 2 million pigs per year, which is a stark contrast to even the largest European pig farms (4,700 pigs on average per farm in Denmark and 1,900 in Germany) (EPRS, 2020). At this farm, the aim is to 'employ fewer people and use more technology', including intelligent feeding systems, manure cleaning robots or infrared (IR) cameras to detect diseases in pigs. These types of technologies will here be referred to as 'Digital Livestock Technologies'[3], or DLTs.

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[1] According to the United Nations, the global population in 1950 reached 2.6 billion people, whilst it was projected to reach 8 billion people on 15 November 2022. www.un.org.
[2] https://www.reuters.com/article/us-china-swinefever-muyuanfoods-change-s-idUSKBN28H0MU
[3] Digital Livestock Technologies relate to what others in the sector of digital agriculture have also called 'smart farming', 'precision agriculture', 'precision livestock farming' (PLF), 'digital farming', etc.

1.2. The potential role of DLTs in improving animal welfare

1.2.1. Monitoring livestock with DLTs

DLTs are designed to assist farmers in monitoring and managing their animals to improve aspects of productivity, and animal health and welfare. They encompass a wider range of digital technologies than so-called 'precision livestock farming' (PLF) technologies (which are known to offer continuous, automatic, and real-time data collection and analysis of a wide range of parameters (Corkery, Ward and Hemmingway, 2013; Berckmans, 2014)) to also include technologies that do not offer continuous monitoring but which can help farmers monitor important parameters e.g., weight monitoring with mobile applications. Current developments mainly focus on health and productivity parameters, especially in the dairy cattle sector (e.g., with heat or lameness detection) (Buller *et al.*, 2020). Many of these systems are based on accelerometers[4] to measure activity (generally in the form of wearables i.e., neck collars, leg or ear tags, or boluses). Such sensors can be used for the early detection of livestock diseases and to monitor, among others, feeding or drinking behaviours, location or environmental parameters such as ammonia levels, CO_2, or temperature (Pastell *et al.*, 2008; Kashiha *et al.*, 2013; Pluym *et al.*, 2013; Chopra *et al.*, 2020; Neethirajan, 2020). Other technologies include camera-based systems that are being developed for various livestock sectors to monitor, for example, feeding behaviours, location, body condition scores, weight, or heat detection. DLTs can also be audio-based and used to monitor stress calls in pigs (Schön, Puppe and Manteuffel, 2004) and in laying hens (Lee *et al.*, 2015), or to detect respiratory diseases in cattle (Carpentier *et al.*, 2018), pigs (e.g., commercially available 'SoundTalks' technology), and poultry (Carpentier *et al.*, 2019). Both camera and audio-based systems have the advantage of being non-invasive and can be used to monitor larger groups of animals. In the pig sector, for example, 49% of publications related to PLF used camera technology, including 2D and 3D images or videos and IR thermography (Larsen, Wang and Norton, 2021).

1.2.2. Linking data to animal welfare

This variety of systems can have important benefits for animal welfare at the individual and group levels. Measuring parameters such as rumination activity in cattle can allow, for example, the detection of feeding deficiencies, which can be indicative of illnesses (Sowell *et al.*, 1998; Weary,

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[4] Accelerometers are sensor devices that can detect and measure accelerating forces on up to three axis units (e.g., tri-axial accelerometers whereby three acceleration sensors are arranged orthogonally along the x-, y- and z-axes) that make up the net acceleration.

Huzzey and von Keyserlingk, 2009). In their study, Sowell et al. (1998) found that morbid steers spent 30% less time at the feed bunk than healthy steers, whilst Weary, Huzzey and von Keyserlingk (2009) found that cows with decreased feeding times were more likely to have clinical metritis. Similarly, measuring lying activity in cattle can give important indications as to their welfare states (Vasseur *et al.*, 2012). How long and how frequently a cow performs lying behaviour are useful indicators of cow comfort, which can be influenced by the type of housing or the presence of painful conditions such as sole ulcers (Haley, Rushen and de Passillé, 2000; Chapinal et al., 2009). In poultry, monitoring flock distribution with digital cameras can provide information on the welfare state of broiler flocks, as this indicator was found to be positively correlated to gait scores (evaluation of walking ability) in broiler chickens (Dawkins *et al.*, 2009; van Hertem *et al.*, 2018). Flock distribution can also be used to indicate anomalies in feeding or water lines as well as environmental conditions in broiler houses (e.g., malfunctions in feeding or drinking, or heating and ventilation) (Kashiha *et al.*, 2013). Finally, another relevant indicator of animal welfare states is vocalisation, which is an important aspect of animal communication (Dawkins, 1998). For example, Weary and Fraser (1995) showed that piglets that were more 'thriving' and well-fed (higher weight and weight gain) had lower frequency calls than piglets that were lighter and which have not been fed for some time. The 'less-thriving' piglets also called more and used longer calls with a greater increase in frequency. The authors found that sows responded to piglet calls and that these responses were stronger to piglets in need. In chickens, about 30 different vocalisations were described, and increased gakel-calls were found after thwarting feeding or dustbathing, indicating the potential of this sound to be linked to forms of frustration (Manteuffel, Puppe and Schön, 2004).

By monitoring these parameters, DLTs have the potential to allow farmers to act ahead of more serious illnesses by detecting anomalies in behaviour patterns, sometimes before the farmers and veterinarians (Kashiha *et al.*, 2013; Berckmans, Hemeryck and Berckmans, 2015; Taneja *et al.*, 2020). This can allow the minimisation of negative consequences to animal welfare and associated costs. The potential of DLTs and the variety of developments have led to discussions around the automation of animal welfare assessments, notably in the context of labelling schemes (Ingenbleek and Krampe, 2022; Stygar *et al.*, 2022).

1.2.3. Automating animal welfare assessments with DLTs

Currently, a variety of welfare assessment tools are available in livestock farming, such as the Welfare Quality® (WQ®) protocols from the European WQ® project. The project aimed to develop standardised animal welfare assessments for different farmed species, including cattle, pigs, or poultry. The protocols are based on four principles: *good feeding*, *good housing*, *good health*, and *appropriate behaviour*. For each principle, several criteria further inform these principles, and for each of these welfare criteria, measures are selected for the assessments (table 1.1). Scores are then calculated based on a bottom-up approach to obtain an overall assessment of animal welfare on particular farm units, which are either rated as *unacceptable*, *acceptable*, *enhanced*, or *excellent*. Whilst the protocols offer a comprehensive assessment of animal welfare, conducting these on farms can take several hours, depending on the species and farm size. These constraints mean that, in the context of assurance schemes, farm assessments are usually conducted yearly, only providing information at points in time (Winckler, 2019). In addition to being time-consuming, there are issues relating to inter-observer reliability and consistency, and these challenges explain the low uptake of these protocols by the food industry (Tuyttens *et al.*, 2021). Using DLTs could help alleviate these challenges by offering more frequent, robust, and consistent data, thereby providing a more accurate picture of animal welfare states. In addition, using DLTs may help reduce the possible biases introduced by manual assessments, as well as reduce cost and time constraints (Blokhuis *et al.*, 2010; Winckler, 2019; van Erp-van der Kooij and Rutter, 2020; Stygar *et al.*, 2022). This, in turn, can help improve transparency within the value chain and build consumer trust in the farming system (Krampe *et al.*, 2021). In the dairy sector, commercially available DLTs such as cameras or sensors can be used to monitor some of the measures included in the WQ® dairy cattle protocol (2009), such as lameness, body condition, or somatic cell counts (Silva *et al.*, 2021)(table 1.1).

Table 1.1: The principles, criteria, and measures, that form the basis for the Welfare Quality® protocol for dairy cattle (2009). In bold are some examples of measures that could be automated with currently existing DLT developments.

	Welfare Criteria	**Measures**
Good feeding	Absence of prolonged hunger	**Body condition score**
	Absence of prolonged thirst	**Water provision**, cleanliness of water points, **water flow**, functioning of water points
Good housing	Comfort around resting	Time needed to lie down, animals colliding with housing equipment during lying down, animals lying partly or completely outside the lying area, cleanliness of udders, cleanliness of flank/upper legs, cleanliness of lower legs
	Thermal comfort	*As yet, no available measure*
	Ease of movement	Presence of tethering, access to outdoor loafing area or pasture
Good health	Absence of injuries	**Lameness** (loose housed animals or tied animals), integument alterations
	Absence of disease	**Coughing**, nasal, vulvar, and ocular discharge, **hampered respiration**, diarrhoea, **milk somatic cell count**, mortality, dystocia, downer cows
	Absence of pain induced by management procedures	Disbudding/dehorning, tail docking
Appropriate behaviour	Expression of social behaviours	**Agonistic behaviours**
	Expression of other behaviours	Access to pasture
	Good human-animal	Avoidance distance
	Positive emotional state	QBA

Providing farmers with more flexibility and time is a common benefit associated with the use of DLTs, in addition to a reduction in stress and physical work since technologies could replace farmers in some routine tasks (Allain *et al.*, 2016; Hostiou *et al.*, 2017; Vik *et al.*, 2019). However, using DLTs does not always result in a reduction of workload. Instead, farmers may be working differently, such as by having to address technical issues or spending time interpreting data (Butler, Holloway and Bear, 2012; Hostiou *et al.*, 2017). This represents just one of the possible consequences of using DLTs and agricultural digital technologies in general. Despite the potential of these tools and the optimism surrounding them (Barrett and Rose, 2022), some authors have also raised concerns over their potential social and ethical impacts, which have received less attention (Rose and Chilvers, 2018; Klerkx and Rose, 2020; Werkheiser, 2020).

1.3. Ethical implications of DLTs

The use of DLTs can change the nature of farmers' work and 'what it means to be a farmer', as farmers may take an increasingly data-driven approach as opposed to hands-on and experience-driven management (Klerkx, Jakku and Labarthe, 2019, p.4). Rose et al. (2021) talk about a changed nature of farm work and identity, with a disconnection between farmer and landscape, potentially leading to mental health issues from decreased work satisfaction. In the broader context of 'big tech', Arogyaswamy (2020) warns against threats to social and political stability, with robots and automation replacing human labour, the Internet of Things (IoT) and Artificial Intelligence (AI) threatening individual rights and societal harmony as well as economic well-being. They emphasise the need to consider how the divide between big and small players is exacerbated by new technologies, as well as to consider issues around data privacy and security. The question of data privacy in digital agriculture is particularly complex, as farm data is collected from and processed by multiple sources and are usually not considered *personal* data but instead are viewed as business or trade data, raising the important question of who should take ownership (Rotz et al., 2019; van der Burg, Bogaardt and Wolfert, 2022). Concerns over job losses and the deskilling of workers have also been raised, as is the risk of creating a 'technological treadmill' that mostly benefits wealthier farms (Werkheiser, 2020).

In the livestock sector, several authors have reflected on how DLTs may change the nature of stockmen's roles, lead to a loss of observation skills, increase mental workload by having to interpret complex data (sometimes from different sources), or negatively impact the human-animal relationship (HAR) (Holloway and Bear, 2017; Werkheiser, 2018). Using DLTs to 'replace farmers' eyes and ears' (Berckmans, 2014, p.190) by facilitating or replacing some of the tasks usually performed manually by farmers could have negative consequences on the HAR and thus on animal welfare, by reducing the frequency and changing the nature of human-animal interactions (HAI) (Waiblinger *et al.*, 2006; Cornou, 2009). Animals may have fewer opportunities to become habituated to people and farmers, particularly on larger farms where opportunities for HAI are already reduced (Rushen, Taylor and de Passillé, 1999; Cornou, 2009). It has also been questioned whether DLTs could help facilitate more intensive types of production systems with fewer opportunities for good animal welfare, by allowing the monitoring of larger numbers of animals with fewer stockmen to look after them (Stevenson, 2017). DLTs could be objectifying; further detaching animals from people and drifting the focus away from the qualitative experiences of animals towards quantifiable aspects such as productivity – turning animals into 'living parts of machinery' (Harfeld et al., 2016, p.409; Bos et al., 2018).

The promise of improved farm animal welfare can thus only become a driver for the use of DLTs if attention is paid to these potential consequences. In fact, the impacts of DLTs on animal welfare in practice are still unclear. According to Dawkins (2021), whether DLTs will improve, or damage animal welfare is likely to depend on three factors: (i) whether stakeholders (including farmers, scientists, consumers, etc.) will come to a shared understanding of the meaning of animal welfare, (ii) whether DLT developments will address the different dimensions of animal welfare and help translate data into practical improvements and (iii) whether DLTs will deliver on their promises when applied in the 'real world'. As many DLTs are currently in the development stages and have not been widely applied, our understanding of these questions is still limited. However, these are important questions to focus on at the early stages of technology development and prior to implementation, to promote technological progress, social acceptance, and benefits to farmers and animals, while limiting negative consequences (Siegrist and Hartmann, 2020).

1.4. Determining the impacts of DLTs on animal welfare

1.4.1. Animal welfare: a multidimensional concept

Animal welfare is a complex, multidimensional notion. Currently, it is still lacking an agreed definition, as different people hold different views about what is important to animal welfare (Weary and Robbins, 2019; Dawkins, 2021). Some, for example, place a greater emphasis on subjective experiences and the animals' affective states[5]. Others believe good health and biological functioning are the greatest priorities, whilst some believe the emphasis should be on promoting aspects of naturalness and animals' ability to express species-specific behaviours (Fraser, 2008). Combining these factors together, Fraser (2008) developed the Three-Circles of Welfare framework to emphasise that animals should live in conditions that allow them to feel and function well, as well as to express natural behaviours. Other approaches to animal welfare exist, with perhaps the most used to date being the Five Freedoms (table 1.2). Whilst the Five Freedoms have influenced animal welfare legislation in the UK (FAWC, 2009), it is now considered outdated due to its strong focus on minimising negative states as opposed to promoting positive ones (Mellor, 2016). Farm animals' ability to express natural behaviours, have appropriate social interactions, or benefit from positive human-animal relationships is indeed integral to their

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[5] According to Mellor (2015, p.3) 'the terms affective states or affects are used to mean the subjective experiences, feelings or emotions that may motivate animals to behave in goal-directed ways and which may accompany success or failure to achieve those goals. These motivational affects may be positive, experienced as rewarding or pleasurable, or negative, experienced as aversive or punishing.'

welfare, in addition to reducing negative experiences such as suffering, stress or pain (Boissy *et al.*, 2007). Other approaches have emerged since, such as the Five Domains Model (FDM), the Quality of Life concept (QoL) or the Welfare Quality® (WQ®) protocols (table 1.2). These acknowledge the importance of animals' ability to live positive experiences (e.g., with the 'mental state' domain of the FDM or the 'appropriate behaviour' principle of the WQ® protocols). Drawing on these approaches, Dawkins (2021, p.2) suggests that 'a possible unifying definition of good welfare is that an animal is (i) in a state of good physical health and (ii) has what it wants', with 'having what it wants' relating to having positive emotions or being in positive affective states.

Table 1.2: Principles/criteria that guide different animal welfare approaches

	Five Freedoms	**Five Domains**	**Quality of Life**	**Welfare Quality®**	**Three-circles of welfare**
Principles	Freedom from Hunger and Thirst	Nutrition	A good Life	Good feeding	Basic health and functioning
	Freedom from Discomfort	Physical environment	A life worth living	Good housing	Affective states
	Freedom from Pain, Injury and Disease	Health	A life not worth living	Good health	Natural living
	Freedom to Express Normal Behaviour	Behavioural interaction		Appropriate behaviour	
	Freedom from Fear and Distress	Mental State			

Recent studies have explored how DLTs could address farm animal welfare based on some of these approaches (Fogarty *et al.*, 2019; Gómez *et al.*, 2021; Larsen, Wang and Norton, 2021; Stygar *et al.*, 2021). They highlighted the important potential of DLTs to address most dimensions of animal welfare for different livestock species (including dairy cattle, pigs, and sheep), and in particular that of the 'behavioural interaction' domain of the FDM (Fogarty et al., 2019) and the good health and feeding principles of the WQ® protocols in the dairy and pig sectors (Stygar et al. 2021; Larsen, Wang and Norton, 2021). Whilst these studies usefully classified technologies under the different dimensions of animal welfare frameworks and acknowledged a lack of focus on the positive aspects of welfare, they generally lacked in-depth reflection about the impacts DLTs may have on animals' affective states. In their study, for example, Fogarty et al. (2019) classified DLTs under each domain of the FDM, including that of mental state (e.g., with heart rate monitors that 'measure' parameters such as stress or fear). However, the mental state domain was 'designed to capture the overall mental experience of the animals, evaluated in terms of the suffering from all impacts considered within the first four domains' (Mellor et al., 2020, p.3). Due to their subjective nature and the difficulties in 'measuring' affects, a more sensible approach may have been to discuss the possible impacts that DLTs that measure objective parameters within the first four domains can have on affective states (for example, how the use of temperature sensors classified under the 'physical environment' domain may impact affects such as thermal comfort).

Whilst using animal welfare frameworks is a useful approach to anticipate the possible impacts of DLTs, one of the reasons why these impacts are still unclear to date is that much of the focus has been on developing innovative DLTs (e.g., developing more sophisticated algorithms to improve accuracy or new methods to monitor animal health and welfare parameters) and ways to encourage their adoption. In contrast, less attention has been paid to whether and *how* farmers make use of DLTs in practice, and whether this changes their approach to animal welfare management. As Ingram et al. (2022, p.7) highlight in their review of priority research questions for digital agriculture: 'rather than a focus on how to encourage adoption of digital technologies per se, the issue is reframed (…) by asking, what are the benefits and how can (and which) farmers derive value?'

1.4.2. Impacts of DLTs on farm management

The question of how DLTs are used by end-users (e.g., farmers) after implementation is particularly important in determining their possible impacts on animal welfare, as a technology that is not used efficiently is unlikely to lead to any positive outcomes. How the potential of DLTs (and digital agricultural technologies in general) can be translated into effective use on farms has, however, been an underexamined question (Eastwood and Renwick, 2020). Despite a wide range of systems being developed, a majority of these are not being used effectively in practice (Lundström, Lindblom and Ljung, 2017). This is likely linked to the complexity of work practices on farms and that of the technologies, as well as the important time, costs, and technical knowledge requirements that these impose (Lundström, Lindblom and Ljung, 2017). For example, one of the perceived barriers to virtual fencing innovation in cattle farming was found to be a lack of ability of farmers to use the technology effectively in relation to improved grazing management due to low feed budgeting skills (Brier *et al.*, 2020). Many DLTs require farmers and their advisors to manage, interpret, and make use of large amounts of complex data. However, their ability to effectively analyse these data to achieve promised improvements was, to date, considered rather limited (Ingram and Maye, 2020). Implementing and effectively using these technologies requires significant practice change shifts and adaptation, as well as an increased learning load (Brier *et al.*, 2020). This changes the spaces of decision-making on farms and affects how farmers interact with their farms (Rose *et al.*, 2018). Exploring how end-users make use of DLTs, as opposed to solely focusing on the binary use or non-use of technology is therefore important (Rose *et al.*, 2022), as the different paths that farmers may take will impact farm animal welfare to varying degrees.

Studies have pointed to a need to consider how farmers *live* with technologies and how they integrate into their work practices, highlighting the different ways in which farmers can make use of the same technology (Lundström and Lindblom, 2021). These different paths are shaped by individual characteristics, including farmers' ability to innovate, to adapt, and their willingness to learn. An example of how impacts on management may differ can be found in a study conducted by Schewe and Stuart (2015) on Automated Milking Systems (AMS). They found that implementing AMS led to different outcomes with varying impacts on animal welfare. These outcomes were influenced by farmers' animal welfare values, goals, and personality traits. For example, farmers who were more willing to give up control over their herd were more likely to report improved human-animal relationships and to give cows 'free choice' (e.g., choosing when to be milked) than those who were uncomfortable giving up control. The latter group of farmers usually reported little to no change in how they viewed or related to their animals.

Other studies have explored the impacts of DLTs on farmers' work routines (Butler, Holloway and Bear, 2012; Hostiou *et al.*, 2017) or on farm economics and productivity (Morgan-Davies *et al.*, 2018), but these have not focused on what farmers had learnt from using DLTs and how this affected their perceptions and approaches to animal welfare management. As Balzani and Hanlon, 2020 (p.18) said: 'creating a culture of continuous learning that is authentic and tailored towards farmers' needs will support knowledge of farm animal welfare and underpin changes in attitudes and behaviour towards enhanced farm animal welfare practices'. Learning plays an important role in farmer decision-making and management, and such learning often occurs during peer-to-peer interactions, where farmers share their experiences and compare views on how new information can be applied to their own farms (Kilpatrick and Johns, 2003; Horseman *et al.*, 2014). How DLTs are used and to what extent they can encourage these interactions, foster learning, and encourage changed management practices are therefore important areas to investigate to understand how their use may impact animal welfare. An approach that lends itself well to exploring these questions is to evaluate the extent to which DLTs can act as boundary objects.

1.4.3. DLTs as boundary objects

Boundary objects are defined as 'objects which are both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites' (Star and Griesemer, 1989, p.393). They are objects that can have different meanings and can be used differently by people depending on the context – there is an aspect of interpretive flexibility. Star (2010) gives as an example a road map, which may guide one group to a campground, whilst for another group (e.g., a group of scientists) it may indicate a series of important geological sites. These maps may be very similar, but their difference lies in how these groups use and interpret that object. As she says: '[o]ne group's pleasant camping spot is another's source of data about speciation' (p.602). Collaboration around boundary objects can help bridge gaps between multiple social worlds by facilitating communication, even when these hold conflicting views about a specific issue (Star and Griesemer, 1989).

Jakku and Thorburn (2010) used the boundary objects concept in the context of agricultural systems, building on a framework to describe the social processes of the participatory development of Decision Support Systems (DSSs, which include DLTs). They explored the outcomes of collaboration between farmers, extension officers, and scientists involved in the development of these systems, and found that DSSs enabled different actors to collaborate despite holding different perceptions of their purpose. Acting as boundary objects, the systems helped bridge the gaps between actors by bringing them together, allowing them to learn from each other and gain a better understanding of the issues addressed by the DSSs. The ability of DSSs to act as boundary objects and foster co-learning among different actors involved in design processes and development of DLTs was also highlighted in other studies (Martin, Felten and Duru, 2011; Thorburn et al., 2011; Eastwood, Chapman and Paine, 2012). These studies emphasised how, by acting as boundary objects, DSSs can foster co-learning and a re-framing of values and beliefs, leading to a shared understanding of the problems addressed.

Conceptualising DLTs as boundary objects to explore their potential to improve farm animal welfare by facilitating discussions and promoting learning and a shared understanding of the meaning of animal welfare thus represents a relevant approach. DLTs are systems that different stakeholders may interact with. This may include farmers, farm advisors, veterinarians, technology developers, researchers, retailers or to some extent, consumers, and even the animals themselves. This diversity of actors means that the expectations and perceptions of the purpose of DLTs will be just as diverse. Farmers may expect from DLTs to help them improve productivity and welfare management, developers may focus on technology performance and ways to increase sales, whilst food retailers may see them as opportunities to improve transparency with consumers and promote leadership in driving animal welfare improvements. Despite this diversity of perceptions, the primary aim of DLTs remains the same (that is, helping farmers monitor their animals more efficiently).

Going a step further in exploring the extent of the impacts of DLTs, the concept of boundary objects can be combined with that of single- and double-loop learning. These concepts were suggested by Argyris and Schön (1978) in the context of organisational learning. They suggest that single-loop learning occurs when 'the error detected and corrected permits the organisation to carry on its present policies or achieve its presents objectives' (p.2-3), whilst double-loop learning occurs 'when an error is detected and corrected in ways that involve the modification of an organisation's underlying norms, policies and objectives.' The concepts of boundary objects and of single- and double-loop learning were used in a study by Duru et al. (2012) on the creation of a modelling and participatory approach to anticipate local grassland-based livestock systems' adaptation to climate change. They explored how the approach fostered learning about adaptation options and found that the use of agro-meteorological and agronomic supports, which acted as boundary objects, helped generate either incremental adaptation or more radical ideas for change. It was less clear, however, what determined these different types of learning, and associated changes in management practices. Farmers' approaches to animal welfare are underpinned by their values, convictions, interests, and norms (te Velde, Aarts and van Woerkum, 2002; Vigors and Lawrence, 2019), thus exploring whether DLTs can foster a greater understanding of the different dimensions of animal welfare and a re-framing of farmers' values and beliefs could help get a better sense of the degree to which animal welfare may be impacted by the use of DLTs.

1.4.4. Implementing DLTs in farm assurance schemes

Prevalent narratives surrounding agricultural digital technologies seem to indicate a linear and rapid change that deeply transforms current farming practices (Rose *et al.*, 2022). However, how farmers engage with technology in practice instead suggests that technological change on-farm is often non-linear, and there are plenty of possible directions that agricultural futures can take (Rose *et al.*, 2022). In their adoption pathway analysis, Montes de Oca Munguia et al. (2021) highlight that adoption processes are dynamic. Farmers take numerous pathways when adopting technologies, and their intentions to use them varies. Over time, farmers may intend to increase the use of DLTs or, on the opposite, decrease or even stop to use them completely, such as when they don't integrate well with their farms (Eastwood and Renwick, 2020). Thus, understanding the processes of implementation of new technologies on farms means going beyond technology acceptance, as often these need to be integrated into complex existing work practices (Lindblom *et al.*, 2017; Lundström and Lindblom, 2018). In addition, technical issues, technology reliability, workload or lack of adequate support can cause farmers mental stress and lead to decommissioning, which further highlights the vulnerability of these technologies (Eastwood, Chapman and Paine, 2012; Eastwood and Renwick, 2020; Neethirajan, 2020; Lundström and Lindblom, 2021).

Since implementing DLTs on farms does not mean that farmers will necessarily positively interact with them, identifying and addressing the challenges of technology implementation when applied to 'the real world' is important to promote uptake and maximise their potential i.e., in helping enhance animal welfare, whilst minimising negative consequences. Of particular interest is the automation of farm animal welfare assessments in the context of farm assurance schemes, which has been the fruit of several discussions (Buller *et al.*, 2020; van Erp-van der Kooij and Rutter, 2020; Ingenbleek and Krampe, 2022; Stygar *et al.*, 2022). These highlighted the possible benefits of using DLTs in this context (also see section 1.2.2.), including improving the transparency of livestock farming practices and having more readily available data to help increase consumers' trust in assurance scheme labels, enabling them to make choices in agreement with their personal values (Hoogland, de Boer and Boersema, 2007).

However, the introduction of DLTs in this context also raised concerns, including uncertainties around the validity of the data, the possibility of applying DLTs in different livestock systems (e.g., extensive systems) or a lack of clarity regarding data ownership (Wiseman *et al.*, 2019; Temple and Manteca, 2020). The lack of validation of DLTs has indeed been identified in several studies and is considered a major barrier to their adoption, as this can impact farmers' trust in the systems (Rose *et al.*, 2016; Gómez *et al.*, 2021; Larsen, Wang and Norton, 2021; Stygar *et al.*, 2021). Trust can also be impacted by the lack of clarity around data governance and concerns over data misuse, which are also commonly raised issues in the wider digital agriculture sector (van der Burg, Bogaardt and Wolfert, 2022).

If not adequately identified and addressed, these challenges could represent important barriers to the introduction of DLTs in farm assurance schemes, and hinder potential opportunities for improved animal welfare management and consumer trust. There is currently a lack of studies that have investigated farmers' perceptions of the use of DLTs in this context, which represents an important knowledge gap considering its potential implications on farmers, consumers, and animal welfare (Stygar *et al.*, 2022). One way to anticipate any unintended consequences and address farmers' concerns is to involve them and other relevant stakeholders in the collaborative development and trialling of DLTs. This could help promote a better understanding of farmers' everyday practices and decision-making processes to develop systems that are more adapted to their needs (Jakku *et al.*, 2019).

1.4.5. Stakeholder participation in DLT developments

The different opportunities and challenges of DLT implementation are tightly linked to the way these are being developed (Rotz *et al.*, 2019). In fact, agricultural digital technologies are often developed with a greater focus on empowering corporate actors as opposed to supporting end-users (e.g., farmers) and making their needs a priority (Rotz *et al.*, 2019). This means that some of these systems are not adapted to end-users and lack relevance to them. Much of farmers' decision-making is based on intuition, which is itself built on tacit, experiential learning, and this knowledge is often not considered when designing DLTs (von Diest *et al.*, 2020). Farmers are not always consulted to bring that knowledge into the design, and this 'top-down' development exacerbates issues around farmers' ability to translate data into effective decision-making, and overall adoption of technologies (Rotz *et al.*, 2019). Farmers adapt to technologies in different ways, thus their role as co-developers should be acknowledged for successful system development (Eastwood, Chapman and Paine, 2009).

As Bronson (2019, p.5) said: 'decisions made by scientists and (technology) designers can impact the directions which food systems, under innovation-led social change, take'. They suggest that an 'equitably realised digital farming transition demands a high level of social rather than simply technical innovation'. Reflecting on what technologies are for and whom they serve is an important aspect of responsible innovation, as is identifying end-users' needs and addressing their concerns (Rose and Chilvers, 2018; Ingram *et al.*, 2022). One way of doing so is to involve them at the early stages of development to address gaps between design and practice in digitalisation (Ingram *et al.*, 2022). Farmers believe that, as primary end-users of these technologies, their involvement in research and innovation processes is important so that their feedback on usability, applicability and relevance can be considered during development and to ensure technologies are developed in their best interests (Regan, 2021). Such inclusive approaches have, however, rarely been utilised (Rose and Chilvers, 2018).

Participatory approaches that allow the early involvement of end-users such as farmers in technology development are thus now increasingly being encouraged as a way to better appreciate how farmers build tacit knowledge and to address developers' limited ability to ground truth information (Ingram and Maye 2020). Increased involvement of end-users can help technology designers develop a greater understanding of their needs and adapt the tools so that they best reflect those needs, and therefore encourage increased adoption and adaptation to new developments (Jakku and Thorburn, 2010; Klerkx and Nettle, 2013; Eastwood *et al.*, 2016). In their study on promoting practice-led multi-actor innovation networks to address laying hen welfare challenges, van Dijk *et al.* (2019) highlighted how a participatory approach allowed relationships to be built between scientists and farmers based on experimental learning and the co-production of knowledge. It allowed different stakeholders to interact, generate novel ideas and test these in a commercial context. They argued that practice-led approaches should be undertaken alongside 'more conventional innovation pathways and other welfare improvements strategies' (e.g., more traditional science-led initiatives), to better address complex problems (p.12). The need to encourage user-centred design was also highlighted by Makinde, Islam and Scott (2019), who promoted the use of Animal-Computer Interaction (ACI) methods to improve the usability and overall utility of technologies both for humans and animals.

There is a variety of participatory decision-making models that highlight the different degrees of participation, from little involvement of end-users to more active engagement where end-users have more 'control' over the decision-making process (see Arnstein, 1969; Reed, 2008; Bell and Reed, 2021). These models were developed to help improve participatory initiatives, as the quality of these processes and how they are managed influence their effectiveness (Bell and Reed, 2021; Regan, 2021). Despite their potential, participatory processes are, however, often considered inadequate in practice (Bell and Reed, 2021). There are many challenges in involving stakeholders in participatory approaches, such as those relating to financial and time commitments, as well as difficulties in maintaining stakeholder engagement, aligning diverging views and priorities, and managing the conflicts that may arise (Reed, 2008; Klerkx and Nettle, 2013; Kerselaers *et al.*, 2015;

Paschen *et al.*, 2021). Regan (2021), for example, explored the readiness of publicly funded researchers in engaging in responsible research and innovation practices and highlighted some of the challenges of participatory approaches and interdisciplinary research. They mentioned that scientists often prioritise scientific knowledge over lay knowledge and noted that institutional support did now always allow inclusion practices, with many researchers seeing stakeholder participation as a burden due to time constraints and lack of support.

Whilst the challenges of participation have been acknowledged in the literature (Reed, 2008; Klerkx and Nettle, 2013; Kerselaers *et al.*, 2015; Paschen *et al.*, 2021), it is less clear how these impact stakeholders' perceptions and attitudes towards the processes and the tools being designed. In particular, fewer studies have investigated the consequences that inadequate management of participatory approaches may have on technology uptake (Valls-Donderis *et al.*, 2014). A lack of engagement, ineffective communication with developers, or systems that do not perform and integrate well within farming systems could hinder end-users' motivation to use DLTs and the trust they have in technology developers. Identifying the potential impacts of challenges met during participatory processes is thus important to develop strategies for well-designed participation and promote the uptake and efficient use of DLTs.

1.5. Gaps and aims of the thesis

The gaps identified in the above introduction highlight the importance of resisting making normative assumptions that the implementation and uptake of DLTs will necessarily lead to improved farm management and animal welfare in a linear fashion. The optimism often associated with their use in the scientific literature, government initiatives or the media (Barrett and Rose, 2022), casts a shadow on the potential ethical and social consequences of using DLTs. Animal welfare is a complex, multidimensional notion (see section 1.4.1), and in the case of farm animals, it is directly influenced by farmers' management decisions. Exploring strategies to enhance farm animal welfare with DLTs thus requires investigating how current technologies can help address animal welfare by informing management, as well as identifying farmers' attitudes towards using DLTs, what their expectations and concerns are, and the potential negative consequences. This thesis thus has a dual aim: to explore how and to what extent DLTs can help address farm animal welfare; and how their uptake can be promoted whilst minimising negative consequences.

To date, there is a lack of understanding as to the extent to which DLTs can impact animal welfare and in particular, a lack of discussion as to how these may impact animals' affective states. There is increased consensus among animal welfare scientists that *good* animal welfare goes beyond minimising health and welfare compromises: it is also about allowing animals to experience positive affective states (Boissy *et al.*, 2007). Affective states relate to animals' subjective experiences, feelings, or emotions (positive or negative), and are a key component of animal welfare (Mellor, 2015). Thus, how farm animal welfare can be enhanced with DLTs will not only depend on their ability to help minimise negative affective states but will also depend on their ability to promote positive ones. This gap led to my first research question (RQ), which is:

RQ1: To what extent do current DLT developments address the different dimensions of animal welfare?

Exploring whether DLTs can help address the different dimensions of animal welfare is, however, only a first step in understanding their potential to improve animal welfare. Animal welfare enhancements will likely only occur if farmers adapt their management decisions in a way that promotes these enhancements. To date, much of the focus has been on developing new DLTs and ways to encourage their adoption. In contrast, little attention has been paid to what farmers have learnt from using DLTs, and how their use may have changed farmers' approaches to animal welfare management and understanding of animal welfare. This gap led to my second research question:

RQ2: To what extent can DLTs promote learning about animal welfare, and what are the impacts on farm management?

The third research question stems from the increased interest in using DLTs to automate animal welfare assessments, due to their potential in reducing the costs, labour, and subjectivity associated with manual assessments. However, considering the challenges of technology implementation and the potential for disruption, it is important to consider how farmers perceive the use of DLTs in this context and to identify their expectations and concerns. This has been underexamined in the context of farm assurance schemes. Doing so may help develop practical recommendations to relevant actors within the food supply chain, to promote farmers' acceptance and use of DLTs in this context, and maximise the benefits for farmers, consumers, and animal welfare, whilst avoiding negative consequences. This led to my third research question:

RQ3: How can DLTs be implemented into practice and what are the challenges?

Finally, one suggestion often put forward to address end-users' (e.g., farmers') needs and concerns in relation to digital technologies is to involve them at the early stages of development. Whilst participatory approaches are often believed to promote technology uptake, there are challenges during these processes, such as time and financial constraints or managing conflicts when stakeholders have diverging interests. Whilst these challenges have been acknowledged in the literature, often this was relegated in favour of an emphasis on developing participatory frameworks. Fewer studies have explored how these challenges may impact farmers' engagement and attitudes towards DLTs. More specifically, fewer studies have explored these issues through case studies during which a variety of stakeholders, including technology developers and end-users, were consulted. Thus, my fourth and last research question is:

RQ4: How do participatory approaches in the development of DLTs influence end-users' engagement and attitudes toward DLTs?

In a nutshell, I ask whether DLT developments *can* address the different dimensions of animal welfare as identified in animal welfare science, whether they *do* in practice, and if so, what the potential negative consequences are in using them. I finally explore how these consequences can be mitigated and how to promote greater collaboration in the development of DLTs. This will allow for making practical recommendations e.g., for policy and industry to develop and implement tools that have the capacity to assist farmers in meaningfully enhancing farm animal welfare.

1.6. Research methods

1.6.1. Research approach

I started this project by taking a pragmatic research approach (Kaushik and Walsh, 2019). In my view, the methodological approach to choose should be one that works best for a specific research question. This may imply a combination of different research methods. Indeed, I consider that qualitative and quantitative methods are complementary strategies, as opposed to being necessarily contradictory. Ontologically, my perception is that reality exists independently of human perceptions but is however *accessible* only through these perceptions and interpretations of individuals. This epistemological position relates to *critical realism* and derives from both objective and subjective ontologies (Zhang, 2022).

Whilst the emphasis on large sample sizes and the confidence that p-values inspire is understandable, qualitative research methods allow not only to understand 'how often', but also 'why' and 'how' a phenomenon occurs (Schwarze, Kaji and Ghaferi, 2020). Whilst considered 'more rigorous', quantitative research methods are often insufficient to assess the role of social constructs. In contrast, qualitative research methods allow to describe procedures, processes and relationships in great detail, and to obtain nuances that are not always obtainable with quantitative research (Schwarze, Kaji and Ghaferi, 2020). Qualitative research can help generate new theories and can help shape researchers' understanding of key theoretical concepts (Bartunek, Rynes and Duane Ireland, 2006), thus it is particularly interesting and suitable for the analysis of social constructions, behaviours, norms, interactions and political implications (Schwarze, Kaji and Ghaferi, 2020).

Using different lenses to approach the complex research questions that this thesis focuses on allowed me to combine the strength of both qualitative and quantitative approaches and help me get a better understanding of my research questions. Combining both methods indeed allows for obtaining different but equally valid dimensions of information – they provide distinctive types of evidence which can offer a powerful source of information (Ritchie *et al.*, 2014). The main advantage of mixing methods is that they can offer a more nuanced picture of complex social phenomena (Ritchie *et al.*, 2014). More specifically, the use of case studies allows for providing a rich and vivid picture of these phenomena as well as their in-depth exploration, as it 'takes the reader of the research into the world of the subject(s)' (Zach, 2006, p.5). For these reasons, this thesis focuses on two case studies and combines both quantitative and qualitative approaches, which are described in the following sub-sections.

1.6.2. Initial plans of the thesis

My initial intention for this thesis was to investigate the impacts of using DLTs on animal welfare using a mixed-method approach. This included designing a 'before-and-after' study that involved farm animal welfare assessments and in-depth interviews with farmers, and a survey to complement the findings. Prior to undertaking this data collection, my first objective was to conduct a review of existing PLF technologies that discusses the extent to which they can help address animal welfare based on the Five Domains Model (Chapter 2). This review was complemented by a workshop conducted in November 2020 and funded by the Animal Welfare Research Network (AWRN) to validate some of the findings. The workshop (of which the outline can be found in appendix 1) gathered over 70 international participants including researchers, NGOs, industries, policy, and farmers. A series of presentations and activities fostered discussions between participants on current developments in PLF for several species (from proofs-of-concept to commercially available technologies) and their benefits to animal welfare and beyond, as well as to identify potential challenges associated with their use and possible solutions. The outcomes of the workshop resulted in the production of a short commentary, which can be found in appendix 2. Both the review (and associated workshop) and the survey were limited to PLF technologies to facilitate data collection and analysis, especially since this term benefits from a clear definition and is commonly used in the digital livestock technology literature (and would thus more likely be understood by farmers responding to the survey). Since PLF represent a major part of DLTs (and as these terms are often used interchangeably in the literature), it is reasonable to assume that the results and discussions stemming from the review and the survey can be extended to the wider DLT area.

At the start of the project, I was able to sign a collaboration agreement with a technology company and a dairy cooperative, which was planning on testing the use of a camera-based monitoring system on 11 dairy farms, to automatically monitor cow lameness and body condition scores as part of their farm assurance programme. This constituted my first case study (more details in section 1.6.4). Initially, my aim was to conduct farm animal welfare assessments before and after the implementation of the camera on these farms, using the WQ® protocols. The idea was to conduct two rounds of assessments on each participating farm at an approximate 12-month interval. These assessments would have been combined with in-depth interviews with participating farmers to investigate whether they had changed their approaches to animal welfare management since using the technology, and to explore their experience implementing and using the system. The idea was to work on an embedded design, whereby the in-depth interviews (qualitative data), would have completed animal welfare assessment results (quantitative data) and help uncover possible links between changed animal welfare scores and changes in management practices. The plan was also to use these interviews as an opportunity to explore farmers' experiences of using the technology as part of the dairy cooperatives' farm assurance programme (Chapter 4).

The first round of in-depth interviews and on-farm animal welfare assessments were conducted as planned, between August 2020 and May 2021, though with a delay imposed by the COVID-19 pandemic and associated travel restrictions. In addition to the pandemic, however, the technology company also encountered technical issues with the camera system, which meant that most of the farmers involved were not able to make use of it by mid-2022. It was therefore not possible to conduct the second round of assessments and interviews, and the project had to be adapted to these circumstances.

These changes also impacted the use of the data collected from the survey. I indeed conducted a survey addressed to UK dairy farmers (appendix 3), which specifically focused on dairy cattle and PLF technologies (as broadening the sample to other livestock species and to the wider DLT category would have made data analyses challenging). The survey was developed in line with the initial plans of this thesis and was comprised of three different sections. The first section aimed at gaining knowledge about PLF adoption in the UK, such as types of devices used and parameters monitored, and factors influencing decisions to adopt PLF. The second section aimed at exploring the impacts of implementing PLF on farm management and animal welfare, whilst the third section was about exploring the challenges of technology implementation and opportunities for support. The survey was distributed online and by post and generated a total of 145 responses (86 online and 59 postal responses). However, due to the challenges encountered and having to adapt my research focus, only the data collected from the second section of the survey (impacts on management and welfare) were used in chapter 3, as the rest of the data did not fit into the other chapters.

1.6.3. Adapting research methods

Whilst it was not possible to conduct the second round of welfare assessments, I decided to conduct the second round of in-depth interviews as planned, between March and April 2022. At this time, only two out of the 11 interviewed farmers had the opportunity to use the technology. Thus, instead of exploring farmers' actual experiences of using the camera and the impacts this had on animal welfare management, I mostly focused on their expectations and concerns. Despite the situation, I saw an opportunity to investigate the impacts that the challenges met by farmers had on their attitudes towards the technology and its implementation, as some of them had expressed signs of frustration due to repeated technology failure and a lack of communication from the developers. In addition to exploring farmers' perceptions of using DLTs for farm assurance purposes, I therefore also explored the issues of technology implementation and participation (Chapters 4 and 5).

To further understand these issues, I decided to select another case study to complete my research. The second case study focused on a smartphone application that was trialled by a UK retailer to allow farm assessors to conduct assessments of animals' emotional well-being (see 1.6.4). The idea of using a multiple-case study design was to obtain more extensive descriptions and explanations of the issues under study, by uncovering new and/or divergent themes, as well as more consistent patterns of behaviour (Zach, 2006).

1.6.4. Case studies

Case study A

At the start of my project, I was able to sign a collaboration agreement with a private technology company and a dairy cooperative that were involved in a project to develop and test a digital camera system to automatically collect Body Condition Score (BCS) and mobility data in dairy cattle. The agreement was signed at a time when farms were in the process of installing the camera and not making use of it. The timeline of this project provided me with an opportunity to undertake a 'before-and-after' implementation study, in line with the initial plans of the thesis. The prospect of being able to contact the farmers involved in the project and conduct on-farm visits made this project a highly relevant case study.

The system was planned to be tested on 11 pilot farms in the UK. Nine of these farms volunteered to test the system as part of the dairy cooperative's farm assurance programme, whilst the other two were brought on board by the technology company to test the technology. All pilot farms volunteered to have the camera installed and did not have to pay for its installation. The system was designed to score dairy cows each time they walked under the camera, which, depending on the farms, was usually placed above a race at the exit of milking parlours. The camera was designed to provide real-time data that could be accessed via an online platform.

The farm assurance programme had an interest in automating body condition and mobility scoring, as these were measures that were required to be performed quarterly by independent scorers on adhering farms. Body condition and mobility in dairy cattle have an important influence on animal health and welfare, as well as on productivity (Whay and Shearer, 2017). However, the manual recording of this data is challenging, as it is time-consuming, costly, and prone to human errors and subjectivity, which are challenges that automation could overcome (Silva *et al.*, 2021).

During the on-farm implementation of the camera, technical issues and external challenges such as the COVID-19 pandemic delayed the project by several months to years. Whilst the first farm had the camera installed in 2018, the issues encountered resulted in the system not being used by the time of the second round of interviews (2022). By that time, the system was operational for only two farms. Issues ranged from power and connectivity issues, hardware and software adjustments, to compatibility issues and unreliable data. Due to the pandemic, these issues were challenging to resolve due to the technical staff's limited ability to visit the farms. Despite the challenges, the re-framing of the study allowed me to gain important knowledge and insight into farmers' experiences, expectations, and concerns about the technology.

Case study B

The second case study was selected due to its relevance to the revised plans of the study, and for its complementarity with case study A. In this case study, a smartphone application was developed by a UK research institute and licensed by a UK retailer to assist with further development and testing. The application was designed to enable supply chain staff (farm assessors) for different livestock species (including cattle, poultry, pigs, sheep, goats, and salmon) to assess animals' emotional well-being and better manage their quality of life.

Like case study A, project leaders (the lead researcher from the research institute and the retailers' project managers) adopted a participatory approach. In addition to farm assessors testing the application, they involved the retailer's supply chain stakeholders (e.g., farmers, farm assessors, veterinarians) in the application's development. For each species, a list of 15 to 20 descriptive terms balanced for positive and negative expressivity (e.g., relaxed, joyful, tense, anxious) was developed based on participants' experience and their discussions of videos showing animals in a variety of environments. This process was guided by the lead researcher who developed the method on which the application was based. After observing the expressive demeanour of animals during farm visits, farm assessors use the application to score each descriptor with sliding scales. The application then integrates these scores through multi-variate statistical analysis. This produces a graph locating visited farms in overall patterns of animal emotional well-being. The graph can be used by farm assessors to make comparisons between farms and to discuss with individual farmers how the emotional well-being of animals on their farms may be managed or improved.

Similarly to case study A, whilst on-farm work was not possible due to time constraints, the interviews conducted with the 17 participants of this project allowed me to obtain rich, diverse, and detailed data about their experience with the trialled technology.

1.7. Thesis outline

The following four chapters of this thesis are constituted by a series of papers that I have either published or submitted to scientific journals. The status of each paper and my contribution to them is specified at the start of each relevant chapter.

In Chapter 2, I conducted a literature review that differentiates between commercially available PLF technologies and those in earlier development stages. I discussed the welfare benefits and risks of using PLF and how they can address farm animal welfare based on the Five Domains Model. More specifically, I associated PLF developments with the first four domains of the FDM (nutrition, physical environment, health and behavioural interactions), and discussed their potential to address affective experiences based on the fifth, 'mental state' domain.

In Chapter 3, I explored the potential of DLTs to impact farm management and animal welfare. Using the case studies and the survey, I investigated the extent to which DLTs could act as boundary objects; facilitating discussions between stakeholders and stimulating different types of learning (single- or double-loop learning). I investigated how these different types of learning outcomes could influence management decisions made to enhance animal welfare.

In Chapter 4, I investigated stakeholders' perceptions of using DLTs in farm assurance schemes. Using one of the case studies during which a DLT was specifically implemented to automate aspects of animal welfare assessments in this context, I explored stakeholders' perceived benefits and the challenges that could promote or hinder the successful implementation of DLTs and discussed the importance of mitigating these challenges.

In Chapter 5, I examined how the participatory development of DLTs can influence end-users' engagement and attitudes towards the participatory processes and use of DLTs. Using the two case studies, I identified and discussed the successes and pitfalls of these processes based on farmers' perceptions and experiences. I made recommendations as to how to manage these approaches in a way that minimises negative consequences on farmers' engagement and motivation to use DLTs.

Finally, I summarised the findings of this thesis and highlighted the contribution to knowledge made by this thesis in a general discussion in Chapter 6, before ending the thesis with the main conclusions of the dissertation (Chapter 7). With this project, I aimed to contribute to the extending critical literature on the digitalisation of agriculture and counter the persisting idea that technological change (and resulting improvements to animal welfare) is a rapid and linear process. I instead concur with counter-narratives that promote greater attention to the possible social and ethical consequences through, for example, greater consideration of important dimensions of animal welfare that have often received less attention, as well as of farmers' and other stakeholders' perceptions and experiences with DLTs. Figure 1.1 summarises the outline of the thesis and how it is structured around the research questions.

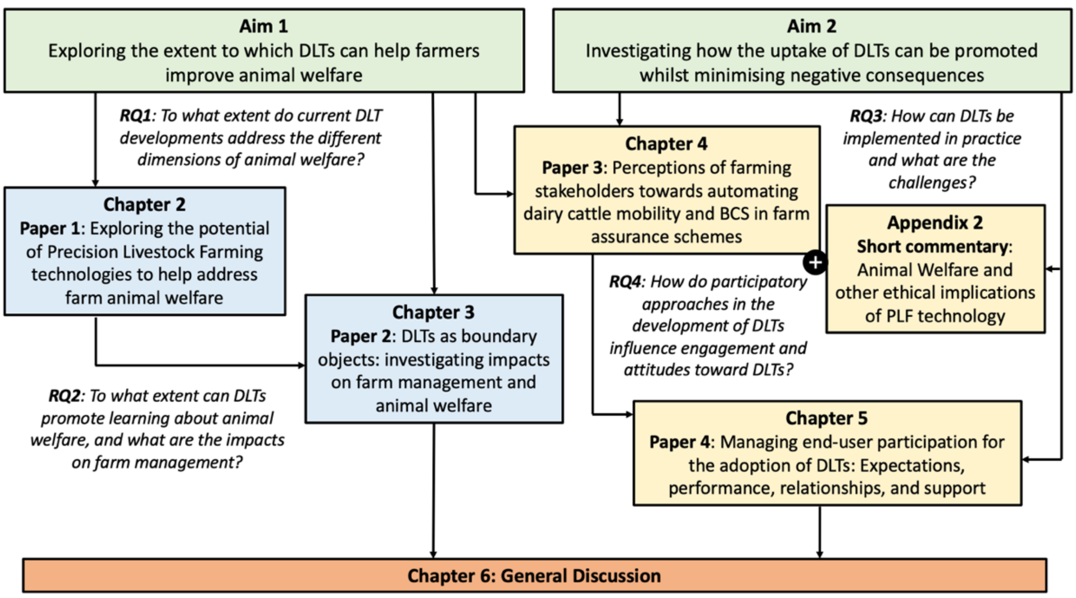

Figure 1.1: Outline of the thesis with chapters and aims

1.8. References

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CHAPTER 2. Exploring the Potential of Precision Livestock Farming Technologies to Help Address Farm Animal Welfare

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Authors' contributions: Juliette Schillings (estimated percentage contribution: 85%): Conceptualisation, methodology, investigation, data curation, writing, original draft preparation, editing. Richard Bennett: Supervision, reviewing, and editing. David Rose: Supervision, writing, reviewing, and editing.

2.1. Information about the paper

This chapter is constituted by a review article that I have published in the scientific journal *Frontiers in Animal Sciences* in May 2021. Starting point of this thesis, the idea of this paper stemmed from a need to explore current DLT developments for different livestock species, and to make a clear distinction between commercially available technologies and systems under development, which, to my knowledge, fewer studies have done before. Considering the overwhelming number of DLTs, I narrowed the focus of this paper to Precision Livestock Farming (PLF) technologies to facilitate data collection and analysis. In addition, this term benefits from aa clear definition[6] and is commonly used in the digital livestock technology literature. Whilst the aim was not to obtain an exhaustive list of PLF developments, this work allowed me to obtain a general vision of the work undertaken in the field of PLF before delving into their possible impacts on animal welfare.

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[6] According to Berckmans et al. (2014, p.190) the objective of PLF is 'to create a management system based on continuous automatic real-time monitoring and control of production/reproduction, animal health and welfare, and the environmental impact of livestock production.'

By classifying the identified technologies under the different animal welfare dimensions of the Five Domains Model (FDM), I was able to get a better understanding of the potential of PLF technologies to address the different dimensions of animal welfare, including that of affective states. I was also able to identify a lack of focus on PLF systems that are able to help promote positive welfare states, as most PLF developments were designed to reduce the occurrence of negative experiences such as diseases or injuries.

This work allowed me to reflect on the complexity of evaluating the impacts of DLTs on animal welfare. Beyond the types of technologies used and the parameters they are designed to monitor, I argued that important factors such as technology validation and performance, technology adoption and implementation by farmers, and associated impacts on farm animal welfare management, must also be considered. The elements of conclusion and questions stemming from the results of this paper are what led me to carry out the work reported in the following chapters (chapters 3, 4 and 5), namely empirical studies centred on end-users' and other relevant stakeholders' experiences with DLTs.

The following sections of this chapter stem from the first manuscript of this thesis. No modifications have been made to the original, published paper, except for minor formatting changes to ensure consistency in the thesis (e.g., table and figure numbers).

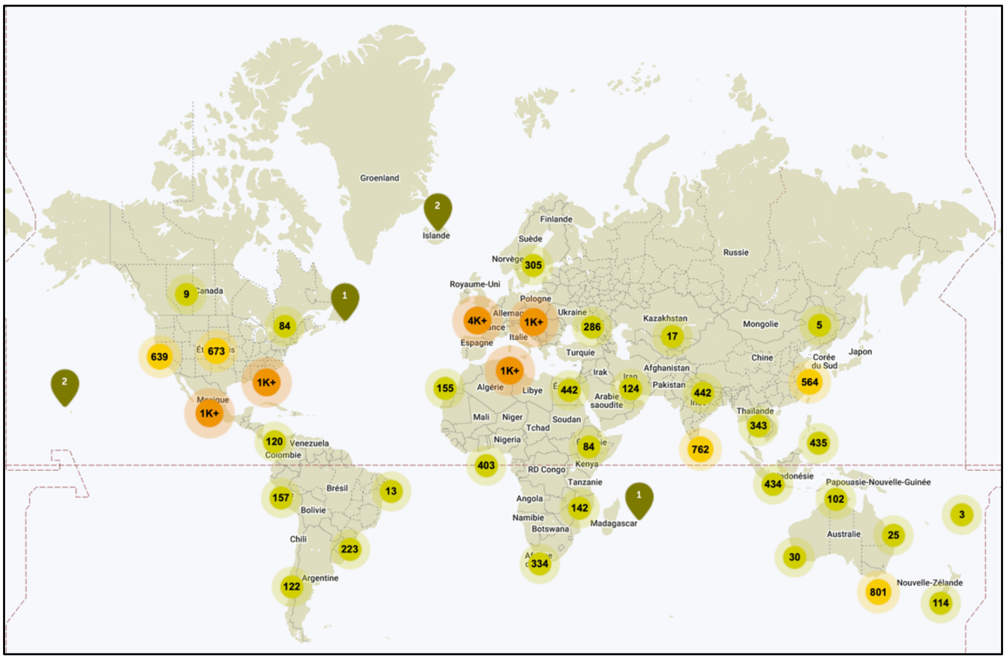

Figure 1.2: This map shows where this paper has been accessed from around the world. As of January 27th 2023, the review cumulated over 25,000 views and had more views than 99% of all Frontiers articles.

2.2. Abstract

The rise in the demand for animal products due to demographic and dietary changes has exacerbated difficulties in addressing societal concerns related to the environment, human health, and animal welfare. As a response to this challenge, Precision Livestock Farming (PLF) technologies are being developed to monitor animal health and welfare parameters in a continuous and automated way, offering the opportunity to improve productivity and detect health issues at an early stage. However, ethical concerns have been raised regarding their potential to facilitate the management of production systems that are potentially harmful to animal welfare or to impact the human-animal relationship and farmers' duty of care. Using the Five Domains Model (FDM) as a framework, the aim is to explore the potential of PLF to help address animal welfare and to discuss potential welfare benefits and risks of using such technology. A variety of technologies are identified and classified according to their type [sensors, boluses, image- or sound-based, Radio Frequency Identification (RFID)], their development stage, the species they apply to, and their potential impact on welfare. While PLF technologies have promising potential to reduce the occurrence of diseases and injuries in livestock farming systems, their current ability to help promote positive welfare states remains limited, as technologies with such potential generally remain at earlier development stages. This is likely due to the lack of evidence related to the validity of positive welfare indicators as well as challenges in technology adoption and development. Finally, the extent to which welfare can be improved will also strongly depend on whether management practices will be adapted to minimise negative consequences and maximise benefits to welfare.

2.3. Introduction

One of the biggest challenges our society is facing is the ability to feed a growing population, which is expected to reach around 9.7 billion people by 2050, while minimising environmental impacts, ensuring human health (FAO, 2018), and addressing the public's rising concern over animal welfare (European Commission, 2016). In the UK, animal welfare standards have been a key subject of public concern, particularly with proposed changes to trade and agricultural policies in light of Brexit (Main and Mullan, 2017). In addition, there have been government commitments to achieving net zero and other environmental improvements in the *Agriculture Act, Environment Bill* and *25-year Environment Plan*. The *National Farmers' Union*, for example, has set a 2040 target for net zero emissions in the agriculture sector, and the *Agriculture Act* and associated plan to improve farm productivity indicates that English farmers can receive financial support to produce 'public goods' such as environmental or animal welfare improvements (Defra, 2020).

However, meeting these commitments is challenging, not least because global meat production is expected to double by 2050[7]. This increase in production may be achieved by a combination of expansion in animal numbers and increased productivity, which will be particularly important in the poultry and pig sector (Gilbert *et al.*, 2015). While it is not possible to predict precisely what agriculture will look like in 2050 (factors such as income distribution, dietary choices and technological innovations will have an important influence), the FAO suggests that in a 'business-as-usual' scenario, animal herds are likely to increase by 46% globally compared to 2012, with poultry numbers increasing over fivefold, threefold for pigs and twofold for small and large ruminants (FAO, 2018). This increase in animal numbers could make their management more challenging, especially if, as was observed in the EU, the number of farmers continues to decrease (eurostat, 2020). In the UK, while livestock numbers remained stable between 2018 and 2019, the labour force on commercial holdings decreased by 0.3% (Defra, 2019). Having fewer farmers to look after larger numbers of animals may make it more difficult to address animal health and welfare challenges.

As a response to these challenges, the development of new technologies has gained momentum. Among these developments are Precision Livestock Farming (PLF) technologies, which are designed to support farmers in livestock management by monitoring and controlling animal productivity, environmental impacts, as well as health and welfare parameters in a continuous, real-time and automated manner (Berckmans, 2014). A variety of systems using technologies such as sensors, cameras or microphones can directly alert farmers via connected devices (e.g., phones, computers or tablets) about detected anomalies, thus allowing farmers to intervene at an early stage. Research is pointing towards the great potential for these 'smart technologies' to help livestock farmers in monitoring the welfare of their animals and several countries are already investing in their development, reflecting their potential to be part of strategies to move towards sustainable agriculture (Rose and Chilvers, 2018; Norton *et al.*, 2019).

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[7] Food and Agriculture Organization. (2019). Meat & Meat Products. http://www.fao.org/ag/againfo/themes/en/meat/home.html [Accessed December 7, 2020].

While their potential is promising, the use of these new technologies also raises ethical concerns, such as their potential impact on the human-animal relationship (HAR), the objectification of animals, the notion of care and farmers' identity as animal keepers (Bos *et al.*, 2018; Werkheiser, 2018, 2020). The HAR is an important aspect which can influence both animal welfare and productivity. The behaviour of stockpeople, which is influenced by their attitudes towards farm animals, have an influence on animals' fearfulness towards humans, with positive behaviours leading to decreased levels of avoidance and negative handling increasing fearfulness towards humans (Hemsworth and Barnett, 1991; Waiblinger, Menke and Coleman, 2002; Probst *et al.*, 2012). In addition, it also influences productivity. For example, reduced milk yields were found on dairy farms where farmers had more negative attitudes towards interactions with cows during milking (Waiblinger, Menke and Coleman, 2002). Aversive handling was also shown to impact the growth performance of pigs and negative relationships were found between level of fearfulness towards humans and egg production (Hemsworth and Barnett, 1991; Cransberg, Hemsworth and Goleman, 2000). On the other hand, habituation, early positive contact and genetic dispositions can be important factors to influence the quality of the HAR (Mota-Rojas *et al.*, 2020). For example, studies found that young broiler chickens exposed to positive human contact had greater growth rates and that positive attitudes were associated with more use of positive behaviours (Gross and Siegel, 1979; Lensink, Boissy and Veissier, 2000). If PLF technologies are used to facilitate and/or replace certain tasks involving human-animal interactions and to reduce time spent on observing individual animals by 'replacing farmers' eyes and ears' (Berckmans, 2014, p.190), it could be questioned whether PLF could impact the HAR by reducing the frequency of human-animal interactions and impacting farmers' attitudes towards their animals and hence their behaviour. Animals may have less opportunity to become habituated to people and farmers if the frequency of neutral or positive interactions is reduced (this may be particularly true on larger farms where opportunities for human-animal contacts are usually reduced) (Rushen, Taylor and De Passillé, 1999; Cornou, 2009; Mota-Rojas *et al.*, 2020). Similarly, concerns were also raised in regard to the extent to which PLF could redefine the notion of care, and whether farmers' attitudes may shift further towards reducing animals to 'tracking devices' and focus primarily on productivity (e.g., disease prevalence or costs of medical treatments) while overlooking the animal's qualitative experiences (Bos *et al.*, 2018).

Taking these benefits and ethical challenges into consideration, it seems important to evaluate the extent to which these technologies can actually address the issue of animal welfare. The notion of animal welfare is complex to define and, while the focus has long revolved around minimising negative experiences such as pain and suffering, studies in animal behaviour and neuroscience have led scientists to highlight the importance of positive affects in animal welfare (Boissy *et al.*, 2007; Yeates and Main, 2008). Affective states relate to feelings or emotions which can vary in intensity, duration, level of arousal and how pleasant or unpleasant they are. While survival-related affects reflect the animal's internal physiological state (e.g., thirst or hunger), situation-related affects reflect the animal's perception of its external circumstances (e.g., comfort, playfulness, depression, loneliness) (Mellor, 2015a). Positive animal welfare cannot be achieved with a sole emphasis on minimising negative experiences; opportunities to experience positive affects (e.g., by allowing animals to engage in rewarding goal-directed behaviours such as through affiliative interactions, exploring or play) must also be provided (Mellor and Beausoleil, 2015). Taking these aspects into account, the 'Five Domains Model' (FDM) has been developed to facilitate the assessment of animal welfare and considers both negative and positive affective states (Mellor and Beausoleil, 2015). The first three domains (labelled 'nutrition', 'physical environment', and 'health') include survival-related factors, while the fourth (labelled 'behavioural interactions') includes situation-related factors. Based on these four domains it is then possible to evaluate the associated affective consequences within a fifth domain, 'mental state' (Mellor *et al.*, 2020). The method can be updated using the latest scientific evidence in animal welfare and can be used in different animal-related sectors (Mellor, 2017).

Using the FDM as a framework, this study thus aims to understand better the potential of PLF technologies to help address the notion of animal welfare by looking at a non-exhaustive, yet wide range of technologies. To this end, PLF developments in a variety of farmed species were identified along with their development stages to distinguish better between commercially available technologies and technologies that are further away from being fully developed. Secondly, the potential welfare benefits and risks of PLF are explored along with their potential ability to promote/address affective states.

2.4. Methods

2.4.1. Identification of PLF technologies

A combination of methods was used to identify PLF technologies. These include searches on scientific papers databases, visiting technology exhibitions, input from colleagues as well as during a workshop organised by the author. These methods are further described below.

Research papers

Search criteria

The databases *Scopus* (Elsevier) and *Web of Science* were used to search for papers relevant to this study. The search was conducted between February and April 2020. Only research articles were selected, with no limits on date of publication. Each search included: a keyword related to Precision Livestock Farming, a species, and either the words ‘welfare’, ‘health’ or ‘behaviour’ (see table 2.1). Considering the variety of methods that could relate to PLF technologies, the selection of PLF-related keywords was based on categories that were commonly referred to in related literature reviews (Benjamin and Yik, 2019; Halachmi *et al.*, 2019; Li *et al.*, 2019; Norton *et al.*, 2019; Astill *et al.*, 2020). These include the use of image-based technology (e.g., using 2D or 3D cameras, computer vision, optical flow, thermal cameras), sound (e.g., using microphones or sonars), sensors [e.g., using accelerometers, pressure or infrared sensors (IR)], Radio-Frequency Identification (RFID) and wireless technologies. It is acknowledged that by using these specific keywords and databases, other types of technologies may have been omitted. It was not the goal of this paper to review all possible PLF technologies for all species, but rather to obtain a general view of current developments and discuss how these apply to animal health and welfare monitoring. The species were selected on the basis of being the main species farmed in the UK. To complete our search, relevant papers referenced in review articles and not present in the databases were also considered.

*Table 2.1: List of the keywords used in the search. Each search consisted of one ‘technology’, one ‘species’ and one ‘parameter’, except for ‘Precision Fish Farming’ which was only associated with fish, salmon and trout. An example of search in Web of Science was: ‘TS=(‘Precision Livestock Farming’ AND (cattle OR cow OR beef OR calf) AND (welfare OR health OR behav*r))’.*

Technology	Species	Parameter
Precision Livestock Farming	Cattle, cow, beef, calf	Welfare
PLF	Pig, swine, sow	Health
Smart Farming	Poultry, laying hen, chick*, broiler	Behavi*r
Automat* AND sound	Fish, salmon, trout	
Automat* AND image	Goat, turkey, sheep	
Automat* AND sensor		
Automat* AND vision		
Automat* AND wireless		
Automat* AND RFID		
Precision Fish Farming		

Selection of papers

Only accessible papers written in English were considered. From the author's understanding based on the literature and the workshop organised by the author (of which more details can be found in section 2.4.2), the definition of PLF technologies can be understood differently by different people. In this study, PLF refers to technologies that are, or have the potential to be, automated, and allowing to monitor animal health, welfare, and environmental parameters continuously and in real-time. Technologies such as virtual fencing or milking robots were, for example, not considered in our study. Papers were selected when the aim of the study was to present a method to automatically monitor farm animal health, welfare or behaviour parameters. These included, for example, monitoring lameness, respiratory diseases, heat, body temperature or environmental conditions. Methods at various stages of development were considered, from proof-of-concepts to validated, fully automated systems. Papers were not selected when the purpose was mainly to refine existing models or algorithms such as to improve image resolution or the detection of certain parts of the body (as they were not about PLF systems in themselves). Papers were also not selected when they addressed transport or post-slaughter issues, when they applied to other contexts than farming (e.g., monitoring of wild animals or applications for laboratory studies), or when authors concluded that the proposed methods did not present satisfying enough results for the purpose of their study.

<u>Commercialised technologies</u>

Commercially available PLF technologies were found in several ways, including visiting technology exhibitions, finding mentions in research or news articles, getting recommendations from colleagues, as well as during a workshop organised by the author of this paper (see next section). When mentions of particular technologies were found, the websites of the relevant companies were visited, and technologies were selected when they allowed to automatically monitor health and welfare parameters of farm animals.

2.4.2. Workshop

The workshop, called 'Current developments in Precision Livestock Farming (PLF) technologies: What can we measure and what are the welfare benefits and challenges' was funded by the Animal Welfare Research Network, AWRN and organised by the first author. Over 150 international participants registered for the online workshop, however, places were limited to 100 participants due to the video conferencing software used (Zoom 5.4). Participants were selected on a ‘first come, first served’ basis with the condition of participants having to be members of the AWRN (or currently applying to become a member). Approximately 90 participants logged in at the start of the workshop, which included researchers and students (59% and 15% respectively), industry workers (8%), NGOs (4%), vets (4%), civil servants (4%), assurance schemes workers (4%) and farmers (2%). Whilst this was not assessed specifically through the event registration form, participants’ knowledge and experience in livestock farming were considered relevant (they had to be members of the AWRN and specify their area of expertise e.g., poultry, pigs, dairy (…) farming), and their exposure to PLF technologies was deemed to range from personal interest to expertise (e.g., current area of work). Most attended the workshop activities, and approximately 70 participants remained until the end. Four 30 minutes keynote presentations (including questions and answers) and two, one-hour activities (including presentations of the outcomes by the participants) allowed the participants to discuss current developments in PLF for several species (from proof-of-concepts to commercially available technologies), their benefits, potential challenges (to animal welfare and beyond) and solutions. An outline of the workshop is presented in appendix 1. Participants were split into eight different groups during the activities, each focusing on one or two livestock sectors. During the first activity, participants were asked to discuss up to five commercially available and up to five ‘promising’ PLF technologies that have the most potential to improve animal welfare for their selected species and to qualitatively discuss the chosen technologies’ potential benefits to welfare. Volunteers in each group presented the outcomes of their discussion to the rest of the participants in three minutes each, sometimes using visual support showing notes taken during the discussions (e.g., whiteboard from the Zoom software or via a Microsoft PowerPoint slide). In a second activity, participants (divided into the same groups) were asked to qualitatively discuss the risks and challenges of using PLF technologies (to their species and beyond), and how these could be minimised. Results were presented in the same way as for the first activity. The first author took notes during these presentations and collected copies of the whiteboards or PowerPoint slides where available. The outputs of these discussions, as well as technologies and welfare benefits and risks mentioned during the keynote presentations, were used to complement the findings of this study (e.g., if the author had omitted specific technologies or benefits and risks that were not initially identified). As the outcomes of the workshop related to animal welfare, but also to aspects beyond the scope of this study (since they are closely related with other aspects such as impacts on farmers, consumers and other stakeholders), only the outcomes directly related to animal welfare (PLF technologies, benefits and risks to welfare) were used to complement the findings of this review.

2.4.3. Classification

The different technologies found using the above methods were classified by the first author of this paper with the help of the co-authors and a colleague (expert in the fields of agricultural technologies and animal welfare) in tables according to their type (e.g., image, sensors, sound, RFID, bolus), their application (e.g., detection of lameness or estrus) and their development stage categories. Each table was associated to a Physical/Functional Domain of the Five Domains Model ('nutrition', 'physical environment', 'health' or 'behavioural interactions'). The technologies' potential welfare benefits and risks and their potential to address affective experiences based on the fifth domain ('mental state') were also discussed.

Technology types and applications

To simplify the tables, the 'technology type' category was kept broad. For example, although technically different, accelerometers and infrared sensors were both classified into a broader 'sensor' category. Similarly, some applications were grouped within categories. For example, the applications related to 'feed intake', 'grazing', 'jaw movements', 'rumination' or 'bites' were all grouped into the 'feeding behaviour' category. Similarly, 'ammonia concentrations' or 'particle matter concentrations' were classified into the 'air/water quality' category. The category 'disease/parasites monitoring' includes technologies aiming to detect ill animals with diseases/parasites such as Bovine Respiratory Disease (BRD) or sea lice in salmon. 'Activity' included behaviour monitoring such as walking, standing, lying or swimming. The technologies were classified according to the specific aims of the papers. For example, when the aim was to determine whether a technology could accurately detect walking and lying patterns, the technology was placed into the 'activity' category within the 'behavioural interactions' domain. Similarly, when the specific aim was to accurately detect estrus in cattle, the technology was placed into the 'estrus' category within the 'health' domain, even if the technology was based on activity data.

Development stages

The development stage categories were inspired by the Technology Readiness Levels (TRLs) developed by the National Aeronautics and Space Administration (NASA). The technologies were assigned within three categories which are broadly comparable with TRLs: 'proof-of-concept phase' (P1), 'validation phase' (P2) and 'commercialisation phase' (P3). Technologies were assigned into the P3 category when the systems were commercially available. Papers which included steps to validate specific technologies or where further papers were published to validate the method were assigned into the P2 category, while those which did not were classified into the P1 category. When several papers addressed a similar application with a similar type of technology, only the highest category was shown. It is acknowledged that the grouping into wider categories may not allow to precisely reflect the state of development of each different type of technology, especially as developments and further validation may have occurred between the initial search and the writing of the paper or may have been omitted due to the restricted number of keywords. Instead, it allows to obtain an overview of current developments and to discuss their potential to address animal welfare.

Welfare implications

The classification into the different domains was based on the updated Five Domains Model (FDM) table developed by Mellor *et al.* (2020). Classification under the first four physical domains was based on the parameters monitored by the technologies (e.g., technologies monitoring feeding behaviours were classified into the 'nutrition' domain, while technologies monitoring lameness were classified under the 'health' domain). Discussions on affective states were based on the FDM table which provides examples of positive and negative factors with their associated inferred negative or positive affective experiences from the fifth domain. For example, under the 'physical environmental conditions' section of the table, 'air pollutants: NH_3, CO_2, dust, smoke' is associated with the negative affects 'respiratory discomfort' (e.g., breathlessness, air passage irritation/pain). For this reason, if a technology was designed to help farmers monitor air pollutants such as NH_3, the author suggested that the use of such technology could have an impact on respiratory discomfort. Similarly, a technology monitoring water intake would have been suggested to have a possible impact on the associated negative affect 'thirst'. Where there were many affects associated with specific factors, only a few examples were suggested to avoid lengthy paragraphs. For example, the FDM indicates that the presence of injuries or diseases may be associated to the following negative affects: pain (many types), breathlessness, debility, weakness, sickness, malaise, nausea and dizziness. To avoid listing all possible affects, the authors selected either those related to a specific condition (such as breathlessness related to respiratory diseases) or those that were most likely to be understood by a wider audience (such as feelings of sickness resulting from diseases). Finally, welfare benefits and risks were discussed both in relation to the specific domains and across domains in a separate section (section 2.5.6). These were identified in the research papers found in this study, technology company websites, within the wider PLF literature and during the workshop.

The presented results mainly stem from the literature review, except where specified (e.g., workshop outcomes strengthening or adding to the reviewed literature).

2.5. Results

2.5.1. Research paper selection

The search revealed 793 research articles in total. After manual selection of papers which we considered relevant to our study, we retained 247 papers. Excluded papers included those that did not focus on specific PLF technologies, papers related to technologies other than PLF, papers that were not accessible or that were in a language other than English. Excluded papers also included duplicates, papers that did not relate to farming or to the species of interest (such as wild or laboratory animals) or that addressed stages of production which we did not consider in this review (e.g., slaughter). A number of excluded papers also included those that were not related to animals (e.g., human medicine). Selected papers included 101 papers related to cattle, 68 to pigs, 37 to poultry, 15 to fish and 26 to other species (including turkeys, goats and sheep).

In the following sections, technologies relating to the physical/functional domains of the Five Domains Model are described along with a discussion on their domain-specific welfare implications based on the fifth domain. These are followed by a section (2.5.6) on welfare benefits and risks across domains.

2.5.2. Nutrition

The monitoring of drinking and feeding behaviours (which includes grazing, ruminating, jaw movements, chewing, or feed intake), and gastrointestinal health were the main applications related to the 'nutrition' domain (table 2.2). The cattle sector appears to benefit from a wider variety of PLF technologies at later development stages in comparison to other species, although commercially available technologies can also be found for pigs, poultry and fish. For small ruminants, technologies mainly range from the proof-of-concept phase 'P1' to the validation phase 'P2'.

Table 2.2: Development stages of PLF technologies related to the 'nutrition' domain of the Five Domains Model for different species (expressed in phases - P1: proof-of-concept stages; P2: validation stages P3: commercialisation phases).

Application	**Species**	**Technology developments**				
		Bolus	**Image**	**RFID**	**Sensors**	**Sound**
Drinking behaviour	Cattle	**P3**	-	P2	**P3**	-
	Pigs	-	P1	P2	**P3**	-
	Poultry	-	P1	-	**P3**	-
	Turkeys	-	-	-	**P3**	
Feeding behaviour	Cattle	-	**P3**	-	**P3**	P2
	Fish	-	**P3**	-	-	**P3**
	Goats	-	-	-	P2	P1
	Pigs	-	P2	**P3**	-	-
	Poultry	-	P1	P2	-	P2
	Sheep	-	-	-	P2	P1
	Turkeys	-	-	P1	P1	-
Gastrointestinal health	Cattle	**P3**	P2	-	-	-

Commercially available technologies

In cattle, smart camera systems using computer vision combined with deep learning can monitor eating time and feed availability at group level, while neck collars equipped with 3D accelerometers continuously monitor rumination and eating time in individual animals. Gastrointestinal health can also be monitored using boluses sitting in cattle reticulum which measure pH and temperature. In pigs, RFID ear tags are used as part of electronic feeding systems, while in the aquaculture sector, hydroacoustic-based technologies and cameras combined with machine learning allow to monitor fish pellet consumption and appetite. Finally, water consumption can be monitored with commercially available boluses in cattle and with sensors in cattle, pigs and poultry.

Technologies in development

Other systems which are currently in the development stages (categories P1 to P2) can monitor ingestive behaviours in free-ranging cattle, goats and sheep using acoustic monitoring (Navon *et al.*, 2013; Chelotti *et al.*, 2016). In poultry, Aydin (2016) developed a sound-based monitoring system to detect short-term feeding behaviours of broiler chickens by recording pecking sounds. RFID systems have been used to monitor feeding patterns in pigs (Maselyne, Saeys, *et al.*, 2016; Adrion *et al.*, 2018), turkeys (Tu *et al.*, 2011) and laying hens (Li *et al.*, 2017). Image analysis and binocular vision techniques have been developed to monitor feeding in pigs (Yang *et al.*, 2020) and poultry (Xiao *et al.*, 2019), while sensor-based systems can monitor feed intake in goats (Campos *et al.*, 2019) and turkeys (Chagneau *et al.*, 2006). Technologies at phase P2 also introduced the possibility to use 3D-vision to automatically assess reticulo-ruminal motility in cattle (Song *et al.*, 2019). Finally, drinking behaviour can be monitored using RFID in pigs (Maselyne, Adriaens, *et al.*, 2016) and a combination of sensors and RFID have been used in cattle (Williams *et al.*, 2020). Accelerometers have been used to monitor drinking in calves (Roland *et al.*, 2018), while camera-based systems have been developed to monitor drinking behaviour in pigs (Kashiha, Bahr, *et al.*, 2013) and chickens (Xiao *et al.*, 2019).

Welfare implications

Using PLF to monitor drinking and feeding behaviours and gastrointestinal health could help provide additional support to minimise the experience of survival-related negative affects such as thirst, hunger or gastrointestinal pain. As changes in drinking or feeding patterns can be indicative of health compromises such as diseases (Nicol, 2011), we suggest that feelings of sickness could be minimised provided that farmers are taking adequate management decisions based on the data (e.g., providing animals with appropriate resources or treatment). In parallel, positive affects such as comfort of good health, gastrointestinal comfort and pleasures associated with drinking and eating could be promoted. However, studies suggest that positive affective states relating to most survival-related factors are usually short-lived (Mellor and Beausoleil, 2015), hence these technologies may mainly have an impact on the negative-to-neutral valence range.

2.5.3. Physical Environment

Table 2.3 shows that air or water quality, animal crowding and distribution and heating/ventilation are the main applications related to the 'physical environment' domain. The monitoring of environmental factors is generally based on image and sensor technologies in the fish, poultry and pig sectors, most of them being commercially available.

Table 2.3: Development stages of PLF technologies related to the 'physical environment' domain of the Five Domains Model for different species (expressed in phases - P1: proof-of-concept stages; P2: validation stages P3: commercialisation phases).

Application	**Species**	**Technology developments**				
		Bolus	**Image**	**RFID**	**Sensors**	**Sound**
Air/Water quality	Fish	-	-	-	**P3**	-
	Pigs	-	-	-	**P3**	-
	Poultry	-	-	-	**P3**	-
Crowding/Distribution	Fish	-	**P3**	-	-	-
	Poultry	-	**P3**	-	-	-
Heating/Ventilation	Pigs	-	P1	-	**P3**	-
	Poultry	-	P2	-	**P3**	-

Technology developments

The monitoring of air/water quality includes the detection of a variety of parameters such as toxic molecules concentrations, pH, CO_2, temperature or oxygen levels which can have important impacts on animal health and welfare. Sensors are commercially available to measure these environmental variables in the aquaculture, poultry and pig sectors. They are also available to monitor heating and ventilation in pig and poultry barns, while image-based systems using animal postures or distribution are still in early development stages (P1 to P2) (Shao, Xin and Harmon, 1997; Xin, 1999; Kashiha, Pluk, *et al.*, 2013). Finally, animal distribution can be detected with commercially available cameras in the aquaculture and poultry sector.

Welfare implications

Monitoring environmental parameters could help address negative affective experiences by minimising thermal, physical, respiratory and olfactory discomfort due to inappropriate temperatures or, for example, inappropriate levels of ammonia. Ensuring optimal environmental conditions could benefit welfare by minimising risks of infectious and respiratory diseases and heat stress, as well as promoting feelings of comfort. In addition, monitoring animal distribution can also indicate welfare compromises or equipment malfunctions (e.g. heating or ventilation systems) (Kashiha, Pluk, *et al.*, 2013). The potential impacts on survival-related affective experiences remain within the negative-to-neutral valence range.

2.5.4. Health

Technologies at different development stages monitor parameters related to the 'health' domain, from specific diseases to foot health and stress, as well as physiological parameters such as heart rate or temperature. Most commercially available technologies appear to apply to cattle, but they can also be found for pigs, poultry, as well as for sheep and fish (table 2.4).

Table 2.4: Development stages of PLF technologies related to the 'health' domain of the Five Domains Model for different species (expressed in phases - P1: proof-of-concept stages; P2: validation stages P3: commercialisation phases).

Application	**Species**	**Technology developments**				
		Bolus	**Image**	**RFID**	**Sensors**	**Sound**
Birth (farrowing,	Cattle	**P3**	-	-	**P3**	-
calving)	Pigs	-	-	-	P2	-
Body condition	Cattle	-	**P3**	-	-	-
	Pigs	-	**P3**	-	-	-
Disease/parasites	Cattle	-	P1	-	P2	P1
monitoring	Fish	-	**P3**	-	-	-
	Poultry	-	P2	-	P2	P1
Estrus	Cattle	**P3**	**P3**	P1	**P3**	P2
	Pig	-	**P3**	-	P1	-
	Sheep	-	-	P2	-	-
Feather damage	Poultry	-	P1	-	-	-
Foot health	Cattle	-	**P3**	-	**P3**	P1
	Pigs	-	P2	-	P1	-
	Poultry	-	P2	-	P1	-
	Sheep	-	-	-	P2	P2
Physiology	Cattle	**P3**	P1	-	**P3**	-
	Fish	-	-	-	P1	-
	Pig	-	-	P1	-	-
	Poultry	-	P1	-	P1	-
	Sheep	-	-	-	P2	-
Sneezing/Coughing	Cattle	-	-	-	-	P1
	Pigs	-	-	-	-	**P3**
	Poultry	-	-	-	-	P1
Stress/Pain	Fish	-	P1	-	-	-
	Pigs	-	P1	-	-	P1
	Poultry	-	-	-	-	P1
	Sheep	-	P1	-	-	-
Weight	Cattle	-	**P3**	-	-	-
	Fish	-	**P3**	-	**P3**	-
	Pigs	-	**P3**	-	**P3**	-
	Poultry	-	P1	-	**P3**	P1

Commercially available technologies

In cattle, body-mounted accelerometers can be used to detect calving, estrus and lameness based on activity data, while cameras combined with machine learning can help determine standing heat, body condition scores (BCS), assess lameness and estimate weight. Boluses placed in the reticulum can also be used to monitor estrus, calving and physiological factors such as body temperature or pH, and ear sensors can monitor temperature. In the pig sector, camera-based systems can determine BCS, estrus and weight, while microphones placed in barns can detect coughing sounds and monitor respiratory health. In aquaculture, image-based systems can allow the detection of sea lice, and sensors and cameras can estimate fish growth. Finally, automatic weighing systems are available to detect the average weight of poultry flocks.

Technologies in development

Growth rate can be measured in broiler chickens using technologies at development stages ranging from P1 to P2, using sound analysis (Fontana *et al.*, 2015, 2017) or 3D cameras (Mortensen, Lisouski and Ahrendt, 2016).

Estrus in cattle can be monitored based on individual vocalisations and caller identification (Röttgen *et al.*, 2020) or with proximity loggers (Corbet *et al.*, 2018). This can also be monitored using RFID technology in sheep (Alhamada *et al.*, 2016), while sensor-based systems can detect pig farrowing (Manteuffel *et al.*, 2015; Pastell *et al.*, 2016; Liu *et al.*, 2018).

Diseases such as mastitis in cattle or campylobacter infection in chickens can be monitored using sensor, sound and image-based technologies at phases P1 and P2 both in poultry (Okada *et al.*, 2014; Banakar, Sadeghi and Shushtari, 2016; Colles *et al.*, 2016; Grilli *et al.*, 2018) and cattle (Steensels *et al.*, 2016; Vandermeulen *et al.*, 2016; Yazdanbakhsh, Zhou and Dick, 2017; Zaninelli *et al.*, 2018; Watz *et al.*, 2019).

Physiological parameters such as respiration rate, temperature or heart rate can be monitored in cattle using image or sensor-based technologies at development stages P1 to P2 (Nogami *et al.*, 2013; Stewart *et al.*, 2017; Strutzke *et al.*, 2019) as well as in poultry (Hyun, Yeong and Wongi, 2007; Xiong *et al.*, 2019), fish (Martos-Sitcha *et al.*, 2019) and sheep (Dos *et al.*, 2018; Fuchs *et al.*, 2019).

Lameness can be detected in pigs using images and sensors (Pluym *et al.*, 2013; Stavrakakis *et al.*, 2015), while gait scores can be evaluated in poultry using optical flow and sensors (De Alencar Nääs *et al.*, 2010; Dawkins *et al.*, 2017; Van Hertem *et al.*, 2018). Sensors can be used to detect lameness in sheep (Shrestha *et al.*, 2018; Kaler *et al.*, 2020) and sound-based systems to monitor lameness and foot lesions in cattle (Volkmann, Kulig and Kemper, 2019).

Technologies in the P1 and P2 phases can monitor coughs in cattle (Carpentier *et al.*, 2018) and sneezing in poultry using sound-based technologies (Carpentier *et al.*, 2019). Similarly, stress or signs of pain can be monitored in pigs (Schön, Puppe and Manteuffel, 2004) and poultry (Lee *et al.*, 2015), as well as by using camera-based technologies in fish (Israeli, 1996), pigs (da Fonseca *et al.*, 2020) or sheep using facial recognition (McLennan and Mahmoud, 2019). Finally, image processing can be used to detect asphyxia in sows during parturition (Okinda *et al.*, 2018) or to predict feather damage in poultry (Lee *et al.*, 2011).

<u>Welfare implications</u>

The identified technologies could help address animal affective experiences such as pain, weakness or sickness emanating from diseases or physical injuries. For example, the early detection of coughing can indicate the onset of respiratory diseases which, if treated adequately, have the potential to prevent the experience of breathlessness which can cause significant threats to welfare (Beausoleil and Mellor, 2015). Similarly, monitoring foot health or predicting feather pecking outbreaks in poultry could help minimise painful experiences provided that appropriate management decisions are taken. This in turn could promote feelings of comfort linked to good health and functional capacity. In some cases, the automatic detection of estrus, whilst mostly beneficial for productivity, could reduce the need for stressful handling (e.g., in pigs), hence potentially addressing negative affective states such as anxiety or fearfulness. As for the 'nutrition' and 'physical environment' domains, the impacts on affective experiences remain within the negative-to-neutral valence range. As highlighted both in the literature and during the workshop, the early detection of diseases could help reduce their spread and support management decisions such as early interventions, better colostrum management, reducing the use of antibiotics, reducing stressful handling or preventing injurious events such as feather pecking.

2.5.5. Behavioural interactions

Many PLF technologies are based on animal activity patterns, such as lying, walking/swimming or standing. As shown in table 2.5, commercially available systems to monitor activity have been developed for most farmed species, particularly using image- and sensor-based technologies. Other technologies have been developed to detect agonistic behaviours, as well as social interactions and maternal behaviours in pigs, cattle and poultry. However, those generally remain at earlier development stages (P1 to P2).

Table 2.5: Development stages of PLF technologies related to the 'behavioural interactions' domain of the Five Domains Model for different species (expressed in phases - P1: proof-of-concept stages; P2: validation stages P3: commercialisation phases).

Application	**Species**	**Technology developments**				
		Bolus	**Image**	**RFID**	**Sensors**	**Sound**
Activity	Cattle	-	P2	-	**P3**	-
	Fish	-	**P3**	-	P1	**P3**
	Goat	-	P1	-	**P3**	-
	Pigs	-	**P3**	-	P2	-
	Poultry	-	**P3**	P2	P2	-
	Sheep	-	-	-	**P3**	-
Agonistic behaviour	Cattle	-	-	-	P2	-
	Pigs	-	P1	-	P2	-
HAI	Poultry	-	P1	-	-	-
Excessive mounting	Pigs	-	P2	-	-	-
Nest building	Pigs	-	-	-	P1	-
Nesting	Poultry	-	-	P2	-	-
Nursing	Pigs	-	P1	-	-	-
Social interactions/	Cattle	-	P1	P2	P1	-
relationship	Sheep	-	-	**P3**	-	-
Perching	Poultry	-	-	P2	-	-

<u>Commercially available technologies</u>

Accelerometers are mostly available for ruminants and are usually attached to the animals' bodies and allow to monitor behaviour, location or postures of individual animals such as lying, standing or walking. Image-based systems can be found in the aquaculture, pig and poultry sectors, whilst hydroacoustic-based systems allow to monitor fish movements. In sheep, pedigree match makers using RFID tags can be used to identify the maternal pedigree of lambs and to monitor behaviour traits of lambs and ewes in extensive systems, which could provide information on potential changes in relationships (Brown, Swan and Mortimer, 2011; Morris, Cronin and Bush, 2012).

Technologies in development

Other technologies at earlier development stages can help monitor activity, such as drones in goats (Vayssade, Arquet and Bonneau, 2019), RFID in poultry (Zhang *et al.*, 2016) and sensors in fish (Martos-Sitcha *et al.*, 2019), pigs (Mainau *et al.*, 2009; Thompson *et al.*, 2016) and poultry (Quwaider *et al.*, 2010; Van Der Sluis *et al.*, 2019). In pigs, tail biting or fighting can be monitored using depth sensors (Lee *et al.*, 2016; Chen *et al.*, 2019), 3D cameras and computer vision (Viazzi *et al.*, 2014; D'eath *et al.*, 2018). Excessive mounting can be detected using image analysis (Nasirahmadi *et al.*, 2016), while nest building can be detected using accelerometer data (Oczak *et al.*, 2015). Nursing behaviour can also be monitored using video analysis (Yang *et al.*, 2019). In cattle, systems have been developed to monitor agonistic behaviours based on sensors (Foris *et al.*, 2019), while image-based technologies can monitor mounting behaviours (Chung *et al.*, 2015; Guo *et al.*, 2019) and social interactions (Guzhva *et al.*, 2016), and accelerometers can estimate locomotor play in calves (Luu *et al.*, 2013). Proximity interactions of individual dairy cows within large herds can also be monitored using local positioning sensor network (Chopra *et al.*, 2020). Image- and RFID-based technologies in the poultry sector allow to monitor human-animal interactions (HAI) (Lian *et al.*, 2019), nesting (Li *et al.*, 2017) and perching behaviours (Nakarmi, Tang and Xin, 2014; Wang *et al.*, 2019). Finally, RFID can be used to explore social behaviour in cattle such as cow-calf affiliations (Swain and Bishop-Hurley, 2007; Boyland *et al.*, 2013).

Welfare implications

The monitoring of specific behaviours and situation-related factors could help to obtain a better understanding of levels of welfare and help evaluate animals' responses to their environment as well as supporting management decisions that may promote the experience of positive affects and minimise negative ones, hence having an impact on the negative-to-positive valence range. Ensuring that animals can engage in natural and rewarding behaviours which are important for their welfare such as nest building or nursing in pigs, social interactions in cows and sheep or nesting and perching in poultry, could indeed help minimise feelings of frustration and promote affects such as feeling maternally rewarded, protected or socially engaged. In pigs for example, monitoring nest building behaviours can help decrease the time sows are kept in farrowing crates without increasing piglet mortality, while monitoring nesting or perching behaviours in poultry can help in housing system design and management. In addition, being able to monitor agonistic behaviours can provide a better understanding of how social relationships (e.g., dominance) are influenced by the animals' environment and encourage measures that will help minimise fearfulness or anxiety by reducing risks of aggression and injuries, while promoting feelings of security. Finally, monitoring the HAR could have important impacts on animal welfare if adequate measures are put in place to reduce the occurrence of negative interactions and promote positive ones (e.g., gentle as opposed to rough handling, or talking softly as opposed to shouting).

2.5.6. Welfare benefits and risks across domains

In addition to the domain-specific welfare impacts suggested above, more general welfare benefits of the identified technologies include the potential to help support management decisions such as early intervention to ensure good health, reduce the use of antibiotics and prevent disease outbreaks, sometimes in systems where monitoring can be difficult (e.g., in extensive systems or where large numbers of animals are kept together). In addition, monitoring animals at the individual level (e.g., using body-mounted devices or boluses) could help better understand the animals' specific needs.

During the workshop, questions were raised as to whether the use of wearable sensors (or those placed inside the animals) could cause discomfort or potential injuries to the animals. Ear tags for example, which are often required for identification and traceability purposes can be a potential source of damage to the animals' ears, with severity depending on the type of tag (Edwards and Johnston, 1999). Although sensors in the form of neck collars do not require the same type of interventions, their potential impacts on animal behaviour and welfare should be further studied. In addition, some of the technologies do not yet allow the monitoring of individuals, but do so at group level (in particular on farms with high number of animals e.g., poultry or fish). While these technologies could be beneficial for the detection of welfare compromises, the interpretation of the data must be done carefully, as management decisions made at group level could be detrimental to the welfare of those individuals whose needs differ from others (e.g., different nutrition or treatment requirements). For example, group monitoring of feed or water intake may not reflect social competition, which may hence be overlooked. Although studies have looked at possibilities to identify competitive interactions at the feed bunk, those were considered not practical due to high costs and labour (Huzzey *et al.*, 2014).

Other concerns relate to the potential to reduce the frequency of visual or physical examination which could impact stockpeople's attitudes and behaviour towards their animals, hence having a potential effect on the human-animal relationship (HAR) and animal welfare. This could be particularly problematic in systems with larger numbers of animals (e.g., poultry or aquaculture), where opportunities to become habituated to people are already limited. Finally, over-reliance on PLF technologies, which was also a concern raised during the workshop, could increase risks of harm if system failures were to occur, in particular where systems are fully automated.

2.6. Discussion

The results from this study indicate that while PLF technologies can have a variety of benefits and may have a good potential to help minimise negative experiences, their current ability to contribute to promoting positive welfare remains limited. In addition, there are welfare risks associated with their use which must be considered, such as their potential impact on the human-animal relationship or on animal management. As Buller *et al.* (2020, p.5) argue, '[i]f it is to make a substantive contribution to addressing genuine animal welfare concerns, PLF technology must therefore address […] the effective monitoring and identification of systemic welfare failures and the active enhancement of opportunities for positive welfare experiences'.

A wide range of commercially available technologies aims to reduce the occurrence and impact of health issues, such as sensors detecting lameness in cattle, microphones monitoring respiratory health in pigs or cameras monitoring the presence of parasites in fish. They are also widely available to monitor and improve productivity such as growth in poultry or estrus in dairy cattle to increase pregnancy rate and optimise insemination. Most technologies monitoring parameters related to the 'nutrition', 'physical environment' and 'behavioural interactions' domains such as feeding or drinking behaviour, air/water quality or activity are also designed with the aim to optimise productivity and to minimise the impacts of diseases. Indeed, changes in feeding or drinking behaviours can indicate signs of illnesses (Nicol, 2011), while inappropriate environmental conditions can be detrimental to animal health and lead to increased mortality (Ge Zhang *et al.*, 2011; Segner *et al.*, 2012). Finally, a variety of technologies that are still in early development stages have focused on preventing the occurrence of undesired behaviours which can cause significant injuries such as tail biting in pigs or feather pecking in poultry (Bilcik and Keeling, 1999; Di Giminiani *et al.*, 2017).

The use of these technologies could have important benefits for welfare if the data are used to support farmers in making effective management decisions. Indeed, PLF could allow the early detection of health issues and reduce the occurrence of negative affective experiences, such as pain resulting from lameness or breathlessness caused by respiratory diseases. In their study, for example, Taneja *et al.* (2020) developed a system which allowed to detect lameness three days before it was visually captured by farmers, with an accuracy of 87%. Berckmans, Hemeryck and Berckmans (2015) showed that respiratory problems in pigs were detected up to two weeks earlier compared to farmers' and veterinarians' routine observations, thanks to a sound-based PLF system. In addition, Kashiha, Pluk, *et al.* (2013) developed a system which allowed to detect issues in broiler houses based on animal distribution indexes, which enables early intervention to minimise impacts on bird welfare. Timely detection of diseases could help reduce the need for antibiotics hence responding to the major global issue which is antimicrobial resistance resulting from the excessive use of antibiotics affecting both animals and humans (Trevisi *et al.*, 2014; McEwen and Collignon, 2018). In addition, PLF could also allow monitoring larger numbers of animals more easily (e.g., using wearable sensors to monitor health status or smart cameras to monitor larger groups), including on extensive systems where the detection of sick or injured animals is often difficult (Rutter, 2014), as well as reducing potential stress resulting from repeated handling and moving of animals (e.g., manual weight detection in pigs) (Kashiha *et al.*, 2014). Furthermore, the use of PLF technologies could also help other actors (e.g., veterinarians or farm advisors) support more efficient and farm-specific management decisions based on the data collected, although this may require improvements in relation to the sharing of data (Rojo-Gimeno *et al.*, 2019).

While health is undeniably an integral part of animal welfare, it does not in itself guarantee 'good' welfare. Studies in neuroscience indicate that negative affective states relating to most survival-related factors, such as thirst or hunger, can at best be neutralised and do not necessarily lead to anything more than short-lived positive welfare states (Mellor and Beausoleil, 2015). Minimising these negative experiences can therefore shift a negative welfare state towards a more neutral one. However, moving towards a positive welfare state requires opportunities to live positive experiences. These include, for example, affiliative interactions, play, or autogrooming, which are believed to have rewarding properties, and have the potential to indicate positive affective states (Boissy *et al.*, 2007). Mellor (2015b) hence suggested that 'welfare reference standards should now be chosen to more strongly reflect a need for such (welfare-enhancing exploratory, foraging and affiliative behaviours) opportunities to be provided'. Some of the technologies identified in this study monitor these types of behaviours (e.g., play and social interactions in cattle, nest building behaviours in pigs or perching in poultry), however, at present, they appear to be mostly at early development stages.

The use of such technologies could help get a better understanding of aspects of welfare that have often received less attention and help support management decisions that could improve animal welfare by promoting positive affects such as feeling engaged, confident or being maternally rewarded, and by minimising negative ones such as fearfulness or frustration from not being able to express natural behaviours. In pig production, for example, sows are often kept in farrowing crates during parturition to restrain their movements and avoid piglets from being crushed. In those conditions, pre-partum sows are not able to perform nest-building behaviours, which they are highly motivated to perform to provide shelter and comfort to their young (Wischner, Kemper and Krieter, 2009). Predicting the onset of farrowing using automated monitoring systems could therefore help in management decisions such as restricting the time sows are kept in farrowing crates only to the critical period where piglets are most vulnerable, hence providing the sows with opportunities to perform those highly motivated behaviours (Oczak *et al.*, 2015), and potentially having an effect on the negative-to-positive valence range.

It could be argued that, while positive animal welfare has gained increased attention in animal welfare science, further research is still required regarding the feasibility, validity and reliability of positive welfare indicators, making their current applicability within welfare assessment protocols difficult. For example, while play behaviour appears to be a valid indicator of positive welfare as it only occurs when all other needs are met (Held and Špinka, 2011), the low incidence of this behaviour in farming conditions makes it difficult to use as part of current welfare assessments (Jensen and Kyhn, 2000; Napolitano *et al.*, 2016). Similarly, while social licking can have positive effects on individual cows, the behaviour might also reflect social tension within a herd (Napolitano *et al.*, 2016). As raised by participants of the workshop, one particular challenge to technology development and implementation in the aquaculture sector may also be related to the existing debate around whether fish can feel pain or experience particular emotions despite growing evidence suggesting that they do (Sneddon, 2019). This limitation in terms of validity and feasibility could explain why technologies with a potential to monitor and promote positive welfare are still in early development stages. Progress is however made in this area: a recent study reviewed promising valid and reliable positive welfare indicators that could be used in welfare assessments of ruminants (Mattiello *et al.*, 2019). These indicators were mostly related to the physical environment, behavioural interactions and mental state domains of the FDM and included, for example, ear or tail posture, half-closed eyes, low-frequency calls or ruminating. From a technical point of view, it would appear that developing technologies monitoring these types of indicators is possible, as a variety of systems identified in the present study have been developed to monitor specific postures, vocalisations or behaviours such as rumination.

Another important aspect to consider in addition to technical feasibility is whether these particular types of technologies would likely be adopted by farmers since the widespread uptake of precision technologies thus far has been rather slow, including in dairy farming as a result of 'innovation uncertainty' (Eastwood and Renwick, 2020). In their study, Vigors and Lawrence (2019) interviewed farmers on their perception of positive animal welfare and found that as a whole, farmers prioritised the reduction of negative experiences, and mostly considered that by doing so, positive welfare would arise as a result. Most of the interviewed farmers considered that different positive welfare indicators such as social interaction or play did not require farmers' direct input or management (except from preventing negative interactions to occur, for example) but that those would happen as a result of other management-based inputs. For this reason, the adoption potential of technologies aimed at monitoring such indicators could be challenging, as they may not be perceived as being a priority. Highlighting the benefits of promoting positive welfare such as the effect on productivity and also on farmers' wellbeing (see Vigors and Lawrence (2019), could help enhance the acceptability of those indicators and therefore the technology adoption potential. Indeed, Lima *et al.* (2018) found that farmers' beliefs (including usefulness and practicality) played an important role in the adoption of Electronic Identification (EID) technology. They suggested that communicating the positive effects of such tools, including on performance, was likely to help enhance technology adoption.

More generally and as raised during the workshop, another potential limitation to PLF technologies adoption may relate to a lack of validation of some technologies which could result in a lack of trust by farmers but also the possibility for welfare-compromising issues to be missed by the technologies. The validation of technologies is usually required to predict how a system would perform under realistic operating conditions, and in the case of PLF, developments must take into account the complexity of living organisms, which are 'individually different, time-varying and dynamic' (Norton and Berckmans, 2017, p.18). This complexity may explain why a wide range of PLF technologies still require further validation. In their study, Larsen, Wang and Norton (2021) found that only 23% of publications related to PLF in pigs were properly validated, and a recent review indicated that only 14% of commercially available sensors in dairy cattle were externally validated (Stygar *et al.*, 2021).

Technology adoption does not, however, guarantee that the technologies will be used in an optimal way in relation to welfare. Firstly, covering the many different ways welfare can be affected would require farmers to invest in multiple systems, as most technologies can only monitor a few parameters at a time and systems are often not connected to each other, adding a difficulty to data interpretation (Knight, 2020). Indeed, there is still a lack of integration of PLF technologies making it more challenging to determine effective mechanisms for intervention (Buller *et al.*, 2020). It is also important to stress that most PLF technologies are monitoring systems, meaning that while they can alert farmers to detected issues, the decision to act on the data provided ultimately lies in the farmers' hands. The extent to which welfare can be improved therefore depends on how the technologies and resulting data are used, and especially whether management decisions are restricted to 'curing' symptoms once they have appeared or whether those decisions would be adapted to prevent issues arising in the first place. Indeed, participants at the workshop believed that there could be a risk that management would be adapted to fit the use of technologies rather than focusing on welfare improvements, such as adapting light hours and levels to fit cameras or having more barren environments to minimise background noises.

In addition, there could be a risk that a greater recognition of issues among livestock keepers would result in greater acceptance of those issues rather than act as a call to action. In the case of lameness in dairy herds for example, which is considered one of the most important welfare issue in dairy farming, a study found that a majority of farmers (90%) did not perceive lameness as being a major issue on their farm, even though the average lameness prevalence was high (36%) (Leach *et al.*, 2010). According to Horseman *et al.* (2014), this may not necessarily be exclusively attributed to farmers not being able to detect lame cows, but could rather be linked to how farmers perceive lameness, as well as their understanding of the benefits of promptly treating lame cows. Indeed, it appears that farmers are more likely to treat severely lame cows more rapidly, leaving simply impaired cows untreated for longer, even though research suggests that it may be more beneficial to treat cows that are less severely lame early (Leach *et al.* (2010) as cited in Horseman *et al.* (2014)). The extent to which welfare can be improved using PLF thus depends on whether the day-to-day management of animal health and welfare will be adapted with the implementation of those technologies.

It is also noted that most technologies monitoring at the individual level appear to be available for dairy cattle, while technologies monitoring smaller animals often kept in highly populated units such as poultry or fish mostly do so at group level (e.g. using cameras) hence ensuring that the 'average' animal receives adequate food, water and environmental conditions (Smaldon, 2020). This is explained by higher numbers of animals with lower financial value per farm, making individual body-mounted devices costly and difficult to implement. On farms where welfare would be assessed automatically at group level, there is a risk that the individual nature of animal welfare might not be sufficiently taken into account if the interpretation of the data is not done carefully. Indeed, assessing welfare parameters at group level does not allow evaluation of whether the measure applies equally to the whole group or to some individuals only, potentially neglecting animals in much lower welfare states (Winckler, 2019). In addition, concerns raised at the workshop related to the design of the technologies which could have an impact on welfare if it is not 'wearer-driven' (e.g., taking aspects into account such as genetic variability or rearing environment). It was also questioned whether facilitating management of larger groups could lead to further intensification.

Another important welfare risk, which was also mentioned at the workshop, relate to the potential impact on the human-animal relationship (HAR). Indeed, most of the technologies identified in this study can be used to replace the need for visual but also physical examination, such as monitoring lameness, environmental conditions or feeding behaviours. Depending on how the time saved in performing these tasks is used by farmers, the potential decrease in human presence and human-animal interactions could have an effect on the HAR. Research indeed suggests that the frequency, intensity and intimacy of human-animal interactions influence the level of attachment or detachment of farmers towards their animals (Bock *et al.*, 2007). This loss of interactions and therefore further detached relationship with animals (which may be more and more perceived as production tools) could result in a decrease in empathy and reduced concerns towards animal suffering. In addition, while some potentially stressful tasks could be avoided using PLF, others which have the potential to strengthen the HAR and that allow animals to be habituated to the presence of humans to some extent may also be decreased. This could reduce human-animal interactions to tasks which cannot be replaced by PLF such as mutilations, hence impacting the HAR negatively (Boivin *et al.*, 1994; Hemsworth and Boivin, 2011). Indeed, Tallet *et al.* (2019) showed that piglets which were tail docked with a cautery iron interacted with unfamiliar humans later than piglets that were not tail docked, and Lürzel *et al.* (2015) observed that calves avoidance distances were higher after disbudding. In their study, Kling-Eveillard *et al.* (2020) found that following the implementation of PLF, some farmers perceived the HAR as having improved, while others believed it deteriorated. They also mentioned concerns that having to manage an increased amount of data may reduce the time farmers spend with animals and impact farmers' observational skills. Concerns relating to the de-skilling of farm staff were also raised during the workshop. While the social impacts of PLF on farmer's work are not detailed here, it is ultimately closely linked to animal welfare, since knowledge and husbandry skills and the ability to identify deviations in behaviours and health compromises are key characteristics of animal care (Hemsworth, Barnett and Coleman, 2009). Farm management supported by the use of PLF should therefore take these potential impacts into consideration, as a negative HAR can be detrimental to animal welfare, but also to farm productivity and job satisfaction (Waiblinger *et al.*, 2006).

While the study aimed at exploring the potential of PLF to help improve animal welfare and the potential risks associated with their use, there are limitations in this study which must be taken into account. As mentioned in the methods section, the identification of PLF technologies was limited to a restricted number of keywords, making it possible to have omitted a variety of technologies. In addition, the different technologies and applications were classified into wider categories with only the latest development stages of all technologies within those categories shown. For this reason, the classification may not reflect the stage of development of all the different types of technologies (although as emphasised in the methods, it was not the goal of the study to determine each existing technology). Finally, it must be re-emphasised that animal welfare is complex, with many variables having a potential impact, whether positive or negative. Using the FDM as a framework helped to capture both positive and negative aspects of welfare, however it remains challenging to predict how the use of technologies will impact on welfare. In addition, the affective states and welfare benefits and risks mentioned in this paper were based on qualitative discussions and evaluation by the authors. Thus, further research aimed at evaluating those positive and negative impacts using quantitative and qualitative methods would be useful to help in technology design, both to maximise potential welfare benefits and minimise the risks. As mentioned by participants of the workshop, further validation of PLF technologies and research on positive welfare indicators as well as a better collaboration between industry, researchers and farmers should also be encouraged, as well as increasing awareness and training of all relevant stakeholders (including training to improve attitudes and behaviour of stockpeople towards animals).

2.7. Conclusion

The potential of PLF to help reduce the duration and/or severity of diseases and injuries in livestock farming systems is promising: technologies can detect health issues at an early stage and help ensure optimal environmental conditions. However, the extent to which current PLF systems can help improve welfare appears to be limited to reducing the occurrence of negative affective states. Some technology developments related to the 'behavioural interactions' domain of the FDM have the potential to help in promoting positive affective states, however, these generally remain at early development stages. This is potentially explained by a lack of evidence regarding the validity of potential positive welfare indicators and the difficulties in measuring them, as well as doubts regarding the adoption potential of such technologies. In addition, the extent to which welfare could be improved depends on whether the data obtained using PLF would be used to adapt management practices while minimising negative consequences (such as the impact on the HAR), and whether actions would be taken to address the root cause of the issues rather than solely focusing on treating the symptoms.

2.8. References

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CHAPTER 3. Digital Livestock Technologies as boundary objects: investigating impacts on farm management and animal welfare

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3.1. Information about the paper

The second manuscript of this thesis was published by the UFAW's (Universities Federation for Animal Welfare) Animal Welfare journal in February 2023. The paper was presented at the ISAE (International Society for Applied Ethology) Congress 2022 which was held on 4th-8th September in Ohrid, North Macedonia. It was also presented at the Seventh Annual Meeting of the AWRN (Animal Welfare Research Network), which was held on 18-19th January 2023 in Newcastle, UK. This paper draws on the reflections made in the first paper of this thesis (Chapter 2), in which I highlighted the need to explore *how* DLTs are used by end-users and how this influences management practices, to better understand the extent of their impacts on animal welfare. I argued that the significance of these impacts would depend on whether management decisions would be restricted to treating symptoms once they occur, or whether these decisions would be adapted in a way that aims at preventing issues from arising in the first place.

The objective of this second paper was to use the boundary objects concept by Star and Griesemer (1989) and that of single- and double-loop learning by Argyris and Schön (1978) to explore what end-users had learned from using DLTs, and how this may have affected their approach to animal welfare management. In this work, I was able to highlight that DLTs can trigger different types of learning, with varying impacts on end-users' approaches to farm management and perceptions of animal welfare. I argued that these impacts may depend on the ability of DLTs to act as boundary objects: bridging gaps and facilitating communication between stakeholders. I highlighted that the extent to which animal welfare can be impacted does not depend on how 'smart' or 'technology advanced' DLTs are, but rather depends on their ability to foster a greater understanding and a re-framing of values and beliefs concerning the different dimensions of animal welfare. This work triggered further reflection on the different ways in which animal welfare can be impacted by DLTs, and further highlighted the need to focus on how end-users interact with DLTs, what they learn from using them, and how this may influence decisions relating to farm animal welfare management.

The following sections of this chapter stem from the second manuscript of this thesis. Only minor modifications have been made to the original, submitted paper, including formatting changes to ensure consistency in the thesis (e.g., table and figure numbers).

3.2. Abstract

Digital Livestock Technologies (DLTs) can assist farmer decision-making and promise benefits to animal health and welfare. However, the extent to which they can help improve animal welfare is unclear. This study explores how DLTs may impact farm management and animal welfare by promoting learning, using the concept of boundary objects. Boundary objects may be interpreted differently by different social worlds but are robust enough to share a common identity across them. They facilitate communication around a common issue, allowing stakeholders to collaborate and co-learn. The type of learning generated may impact management and welfare differently. For example, it may help improve existing strategies (single-loop learning), or initiate reflection on how these strategies were framed initially (double-loop learning). This study focuses on two case studies, during which two DLTs were developed and tested on farms. In-depth, semi-structured interviews were conducted with stakeholders involved in the case studies (N=31), and the results of a separate survey were used to complement our findings. Findings support the important potential of DLTs to help enhance animal welfare, although the impacts vary between technologies. In both case studies, DLTs facilitated discussions between stakeholders, and whilst both promoted improved management strategies, one also promoted deeper reflection on the importance of animal emotional wellbeing and on providing opportunities for positive animal welfare. If DLTs are to make significant improvements to animal welfare, greater priority should be given to DLTs that promote a greater understanding of the dimensions of animal welfare and a re-framing of values and beliefs with respect to the importance of animals' wellbeing.

Keywords: Animal welfare; boundary objects; Digital livestock technologies; learning; positive animal welfare; precision livestock farming.

3.3. Introduction

The development of smart technologies is viewed as a key response to the increased concerns around sustainability (Walter et al., 2017). In the context of population growth and rising demands for livestock products, farm animal welfare is gaining attention (European Commission, 2016). However, ensuring good animal welfare, improved productivity, and minimal impacts on the environment of livestock production systems is ever more difficult as a decrease in the number of farmers makes attending to the needs of an increasing number of animals more challenging (eurostat, 2020). It is for these reasons that Digital Livestock Technologies (DLTs), such as Precision Livestock Farming (PLF) technologies, have gained particular interest, as they allow improved monitoring of animals. By tracking changes in animal behaviour or physical parameters, DLTs can help detect health and welfare compromises at early stages, thus facilitating farmers' work and giving them better control over livestock management (Berckmans, 2014; Kling-Eveillard et al., 2020). There are different forms of DLTs, including wearable sensors (e.g., collars, leg, or ear tags), digital cameras or microphones, that can detect, for example, heat or lameness in dairy cattle, respiratory health in pigs, or environmental parameters in poultry farms. These technologies present many benefits; from minimising risks of diseases or injuries to reducing costs and improving animal productivity and health and welfare in a variety of production systems (Schillings et al., 2021).

Although the benefits of DLTs in relation to animal welfare are often promoted, the extent to which DLTs can help improve animal welfare is still unclear. As Dawkins (2021) suggests, this is likely to depend on how animal welfare is defined, how much it will be considered in technology developments, and whether DLTs will be able to deliver on their promises. Animal welfare is a complex notion that can be understood differently by different people. Such divergence of perception can have a range of implications, as reaching a consensus when defining ethical ways of keeping animals becomes challenging, and initiatives to improve animal welfare may fail (Dawkins, 2021; Fraser, 2008). Whilst historically, reducing harm and negative experiences have often been the focus of animal welfare science, the importance of positive animal welfare, which emphasises the capacity for animals to experience positive affective states and to live good lives, is increasingly highlighted (Boissy et al., 2007; Lawrence et al., 2019; Mellor & Beausoleil, 2015).

Determining how DLTs may impact farm animal welfare should thus not only be based on their capacity to better detect health and welfare compromises. It should also focus on whether tools can foster learning and a shared understanding of the notion of animal welfare, particularly on the importance of promoting positive animal welfare. We suggest that this capacity is likely to depend on the ability of DLTs to act as boundary objects. Boundary objects are defined as 'objects that are plastic enough to be adaptable across multiple viewpoints, yet maintain continuity of identity' (Star, 1989, p.38). They can be 'material' objects or theories and concepts, which, while sharing common definitions and goals, may be interpreted or used differently by different actors (Star, 2010). In their study, Jakku and Thorburn (2010) conceptualise Decision Support Systems (which include DLTs) as boundary objects through which different actors can collaborate and co-learn during their development. By opening discussions and collaborating, stakeholders can increase their understanding of a specific issue, even when holding diverse views about it.

Whilst the concept of boundary objects has, to the authors' knowledge, not been applied in the context of farm animal welfare, studies have investigated the potential of boundary objects to facilitate discussions, knowledge sharing and impacts on management practices in the context of sustainable farming (Hochman et al., 2021; Morris et al., 2020; Zinngrebe et al., 2020). Morris et al. (2020), for example, found that using boundary objects (a simulation tool and board game) fostered learning and changes in livestock management practices by supporting perspective sharing among stakeholders on strategies to transform livestock production. Similarly, a study focusing on the participatory development of a Decision Support System to improve nitrogen fertiliser use in sugarcane production also found that, by acting as boundary objects, the system allowed stakeholders to explore management strategies and co-learn, resulting in changed perceptions of local sugarcane production systems and their management (Thorburn et al., 2011).

By acting as boundary objects, the use of DLTs could thus facilitate discussions between farmers and other stakeholders (e.g., advisors, technology developers, consumers, or retailers), and foster learning around the notion of animal welfare. This could, in turn, lead to changes to management practices with varying impacts on animal welfare. Indeed, learning plays a key role in decision-making and changed farm management practices (Kilpatrick and Johns, 2003; Leeuwis, 2004). The main sources of learning for farmers were found to be mostly unstructured and informal, such as through observation and experience, and through social and business networks and interactions with peers or advisers (Kilpatrick and Johns, 2003). As Kilpatrick and Johns (2003, p.154) note: '[i]nteraction allows farmers to compare views on how information could be applied to their own situations and to test each other's values and attitudes toward making changes as a result of the information.'

Different types of learning can, however, lead to different outcomes. Leeuwis (2004) distinguishes between regular and architectural innovations, the former involving learning about how to make improvements within the boundaries of basic cognitive assumptions and principles (such as norms, goals and values). Such learning can be referred to as 'single-loop learning' (Argyris and Schön, 1978): the process of modifying and improving strategies as a result of detecting errors. In contrast, architectural innovations involve a questioning of these assumptions and principles and a shift in how strategies are framed (double-loop learning). In other words, single-loop learning relates to the 'know-what' and 'know-how' dimensions of knowledge, whereas double-loop learning involves a 'know-why' dimension (Reed et al., 2016a). The impacts of DLTs on animal welfare may thus be greater if they can foster a deeper reflection on farmers' underlying values and norms (double-loop learning), since these influence farmers' motivations to seek more knowledge about animal welfare or to engage in management practices that can support its improvement (te Velde et al., 2002; Vigors and Lawrence, 2019).

Little is currently known about the potential of DLTs to act as boundary objects and the extent to which they can foster learning around the notion of animal welfare, and what the consequences would be for farm management practices. The aim of this study was thus to explore these topics using the concepts of boundary objects and single- and double-loop learning, and to discuss the potential impacts on farm management practices and their significance to the enhancement of farm animal welfare. The study focuses on two case studies during which two different DLTs were tested. The results of a survey were used to gain further knowledge on the impacts of DLTs on farm management practices and animal welfare.

3.4. Material and methods

In this study, qualitative and quantitative approaches were combined to obtain a wider and more in-depth understanding of the possible impacts of DLTs on farm management and animal welfare. The use of case studies allows one to obtain an in-depth understanding of a number of cases in their real-world context, with the hope to result in learning about real-world behaviour and its meaning (Yin, 2011). Combining case studies with a survey can help get a more complete picture of the answers to our research questions.

3.4.1. Ethical considerations

Since the study involved interviews with human subjects and the dissemination of a survey, the research project has been reviewed according to the procedures specified by the University of Reading Research Ethics Committee, which granted ethical clearance for this project. Participation in this research was completely voluntary. The research did not require the collection of information that may have been considered sensitive in terms of confidentiality, or that may have caused personal upset. It did not involve elements of deception, and participants were offered a guarantee of anonymity and secured data storage, and the possibility to withdraw from the study at a date specified in information sheets (provided to interview participants and at the start of the survey).

3.4.2. Boundary objects and learning outcomes

We combined the concepts of boundary objects and of single and double-loop learning to describe the social processes of the participatory development and use of DLTs and to identify the different learning outcomes resulting from end-users' interactions with DLTs. In this study, we conceptualise DLTs as boundary objects, allowing various stakeholders (e.g., farmers, developers, retailers…) to collaborate and co-learn. By facilitating communication between these stakeholders, DLTs as boundary objects can help foster a shared understanding of complex notions (in this case, animal welfare). These learning outcomes may, however, vary depending on whether a change in knowledge, attitudes or practices occurred. We, therefore, used the single and double-loop learning concepts to highlight this distinction and to strengthen discussions on the impacts of using different DLTs (see case study descriptions) on farm animal welfare. Indeed, where a re-framing of values and beliefs occurs (which relates to the concept of double-loop learning), it is likely that management decisions to improve animal welfare will have a more significant impact than if existing strategies are only adapted and not re-questioned (single-loop learning).

3.4.3. Case study descriptions

In-depth, semi-structured interviews were conducted by the first author with stakeholders from both case studies (N=31), using topic guides (see appendix 4 for an example). This method allows to generate large amounts of detail about participants' experiences, whilst allowing the discussion to be guided to address our research questions.

<u>Case study A: Cattle mobility and body condition scoring</u>

A camera system to monitor Body Condition Scores (BCS) and mobility in dairy cattle was developed and tested on 11 pilot farms in the UK, 9 of them trialling the technology in the context of a farm assurance programme. Body condition and mobility are important factors that can influence animal health and welfare, as well as productivity (Whay and Shearer, 2017). These measures are usually undertaken by humans, which poses the risk of introducing biases and errors. Automating these measures was thus seen to reduce these risks while allowing farmers to spot any changes in conditions early (Silva et al., 2021). The system scores cows each time they pass under the camera, which is usually placed at the exit of milking parlours.

Two rounds of interviews were conducted. The first involved all 11 farmers before they were able to use the technology. Interviews were held between August 2020 and May 2021 for 46 minutes duration on average, using the phone or video conference software (e.g., Microsoft Teams) due to COVID-19 pandemic restrictions. The discussions involved health and welfare management, general cattle welfare and farmers' use of DLTs. The second round of interviews was conducted with nine of the 11 farmers, as one farmer had sold their cows during the project, whilst another was not able to install the technology. Two technology developers and a stakeholder involved in the farm assurance programme were also interviewed. These were held for 53 minutes duration on average, using the same platforms, between March 2022 and April 2022. The gap between the first and second rounds of interviews is explained by technical issues in addition to external challenges such as the COVID-19 pandemic, which delayed the project by several months. It also meant that the system was fully operational for only two participating farmers at the time of the interviews. The results and discussions are thus primarily based on farmers' expectations and perspectives; except where specified for those farmers having used the technology. Themes addressed during the second round included changes to management practices and welfare, learning and impacts on attitudes towards animal welfare.

Case study B: Smartphone application

A smartphone application was developed by a UK research institute, and licensed and trialled by a UK retailer, to allow farm assessors to assess animals' emotional well-being by scoring their expressive demeanour. The application can be used in different livestock farming systems, including cattle, poultry, pigs, sheep, goats, and salmon. For each species, a list of 15-20 descriptive terms balanced for positive and negative expressivity (e.g., relaxed, joyful, tense, anxious) was developed participatively by the retailer's supply chain stakeholders (e.g., farmers, farm assessors, veterinarians), based on participants' experience and on a discussion of videos showing animals in a variety of environments. These terminologies were inserted into the application. When visiting a farm, after observing the expressive demeanour of animals on that farm, farm assessors would score each descriptor on sliding scales. The application then integrates these scores through multi-variate statistical analysis and produces a graph locating visited farms in overall patterns of emotional well-being. This graph can be used by assessors to make comparisons between farms and to discuss with individual farmers how emotional well-being on their farms may be managed or improved.

The same topics as in case study A were discussed with participants (N=17) during a single round of interviews held in May 2022, using the same platforms. These lasted 50 minutes on average. The lead researcher, who developed the method on which the application was based, provided contact email addresses for 21 stakeholders of the retailer's supply chains who were involved in trialling the application and who were willing to be contacted by the first author. From the 21 people contacted, 16 stakeholders covering different species subsequently agreed to be interviewed, including farmers, farm assessors, supply chain directors and others involved in the project (e.g., coordinators, project managers). An interview was also conducted with the lead researcher.

Quotes from case study participants were used to support statements in the results and discussion sections. For case study A, we identified farmers as 'farmer 1' to 'farmer 11', and developers as 'developer 1' and 'developer 2'. For case study B, due to the variety of stakeholders, these were identified as 'participant 1' to 'participant 16'.

3.4.4. Qualitative data analysis

Interviews were recorded using a smartphone application or software recording options (e.g., Microsoft Teams). The interviews were transcribed verbatim by the first author, allowing better familiarisation with the data (Braun and Clarke, 2006). The data was then analysed thematically using a qualitative data analysis software (NVivo 12) for coding. Analysis was guided by methods from Braun and Clarke (2006) and Ritchie et al. (2014). First, an initial thematic framework was produced, using a series of themes and sub-themes which covered the aims of the study. The data were then coded into these themes, with new ones emerging throughout the coding process. The data were then sorted, and each theme was reviewed, sometimes resulting in the deletion, or merging of themes. Finally, data summaries were produced for each theme, helping to uncover key elements and underlying dimensions that guided data interpretation.

3.4.5. Farmer survey

To gain further insights into how DLTs could change management practices independently from the case studies described above, we conducted a farmer survey focused on the dairy sector and precision livestock farming technologies[8]. We focused on this specific area because it gave us access to a wide range of commercially available technologies[9]. Since PLF constitute a major part of DLTs, we expect that data interpretation can be extended to the wider area DLTs. The survey was created using Qualtrics (Qualtrics XM Software, Provo, UT). The survey was distributed online using the authors' networks and relevant organisations and institutions, as well as on social media and farming forums. To increase the sample size, the survey was also sent by post to 250 dairy farmers in the UK. Postal addresses were found using the *UK Government list of Registered Dairy Establishments (as at 1 August 2021 to 1 November 2021)*. As the list only provided partial addresses, full addresses were obtained using the search engine *Google*. Addresses from the list were selected randomly. The survey was piloted online with five dairy farmers before distribution, and changes were made based on farmers' comments. Survey responses were anonymous, and an incentive of £1 was donated to the *Royal Association of British Dairy Farmers* (RABDF) per completed response.

A total of 33 questions could be answered by respondents, although this number varied depending on respondents' choices (see questionnaire in appendix 3). The survey was developed as part of a wider study, therefore only relevant results to this study will be discussed. 86 online and 59 postal surveys were completed, leading to a total of 145 responses. 16 respondents, who indicated using DLTs, submitted partial responses. These were taken into account in our results. Some respondents left some questions unanswered. Thus, *N* is used throughout to describe the total number of respondents, and *n* the number of respondents to a specific question. Descriptive statistics were performed on the survey data using the Qualtrics platform and Microsoft Excel.

3.5. Results

The interviews conducted for both case studies indicated that the DLTs used had the potential to act as boundary objects. In this section, we explain how DLTs facilitated connections between

[8] Precision Livestock Farming technologies are DLTs that can monitor parameters in real-time, automatically and continuously.

[9] Extending the survey to all farmed species and to the wider area of DLTs would have made analysing the data less manageable. In addition, the term PLF is commonly used in the literature and thus more likely to be understood by the survey respondents.

stakeholders (e.g., advisors, consumers, and producers) and which type of learning they generated, using the concepts of single and double-loop learning. Whilst both DLTs could facilitate connections, they differed in the type of learning they fostered.

3.5.1. Facilitating connections

In both case studies, it was reported that technologies could indeed facilitate discussions between stakeholders such as farmers and farm advisors (e.g., vets or nutritionists), as well as help bridge the gap between producers and consumers. Participants from case study A mentioned that using the camera, which enables constant and automatic monitoring of BCS and mobility, could help advisors tailor their advice based on the data generated; helping farmers in decision-making to boost productivity and improve animal welfare. As one developer said:

> 'From those two metrics, vets and farmers can derive a lot of information and understand what actions they should take to ensure productivity doesn't decrease and ensure the welfare of the animal doesn't get worse.' (Developer 1)

Similarly, participants from case study B believed that the use of the application had the potential to connect stakeholders such as farmers, farm assessors or vets*,* helping to provide better insight into what happens on farms. As one participant said:

> 'We very much want the farmers to be engaging with it and to be able to get a better insight into what's going on, on their farms. And again, by having the vets do it; to engender those discussions between the vet and the farmer and in turn those discussions between the independent assessor and the vet and the farmer.' (Participant 1)

The application was also generally seen to open discussions between farmers on their management practices, encouraging them to discuss with other farmers what they have been doing and to identify possible improvements based on their scores. As one participant said:

> 'It almost has that level of friendly competition (…) if perhaps you're not in the top end (…) then you want to be asking your colleagues; what are they doing? How can you improve that?' (Participant 7)

The application was also considered a useful conversation tool by participants, as it enabled actors to articulate what they were already thinking internally. One participant, for example, mentioned how the application could help put words on feelings and thoughts. As another participant said:

> 'The proof of the pudding is that you talk to vets and other experts that have used this tool and it very much reflects what they see independently (…) They would go on farm and (…) have that feeling internally without being able to express or articulate it. Actually, the app almost always will merely reflect precisely what you've been thinking.' (Participant 1)

Another benefit of both technologies was their ability to bridge the gap between consumers and producers. In case study A, participants mentioned that by being able to provide evidence on claims about animal welfare, consumer trust in the farming system could be improved. As the stakeholder working for the farm assurance programme organisation said:

> 'We need to have that detail if we are ever challenged on the claims we're making, we want to be transparent and truthful in everything we do, so these technologies help us to have that integrity.'

Bridging this gap was also considered a benefit of application (B). As a participant said:

> 'Often, there's quite a disconnect in this country (…) The farmer has very little understanding of what's important to the shopper, and the shopper, very little understanding of where food is being produced. So, they have a job to try and bridge that gap too.' (Participant 15)

On the biggest value of this application, the same participant added:

> 'I think, getting the message across to consumers (…) to say we care about the animals in our farming systems (…), that it is not just intensive, faceless, big business: it's about real people and feelings and emotions.'

Most participants from case study B also highlighted the ability of consumers to relate to the descriptive terminologies used to generate scores in the application. They saw this as a non-specialist language that consumers can easily visualise and understand e.g., terms such as ‘content’ and ‘distressed’ as opposed to health metrics such as mastitis in dairy cows. It was also considered a way to demonstrate to consumers that the emotional aspects of animal welfare, in addition to minimising negative experiences and promoting good health, were taken seriously. In the same way, conversations about positive animal welfare could also be facilitated with farmers through the application. Reporting on a participant’s experience, the lead researcher said:

> ‘One person said (…) when they come on a farm visit and have quite a few assessments to make (…) and they show (the app) to the farmer; it just opens up a conversation about something that the farmers aren't necessarily used to talking about.’

Both technologies thus have the potential to facilitate connections between stakeholders, helping farmers in decision-making and helping consumers make better-informed choices. In case study B, the application could also foster discussions on other dimensions of animal welfare (e.g., positive animal welfare).

3.5.2. Learning outcomes

By connecting different stakeholders, DLTs have the potential to better inform management and foster learning and increased knowledge around animal welfare. This could have important implications for animal welfare, although the extent of these impacts is likely to depend on the type of learning generated.

Single-loop learning

In case study A, the technology is designed to allow farmers to detect changes in lameness and body condition more precisely and more frequently than the human eye can, especially where large numbers of animals are involved. This allows farmers to act at an early stage, preventing, for example, more severe cases of lameness, which can develop if slightly or moderately lame cows are not detected. Using constant, unobtrusive monitoring and spotting subtle changes, farmers can minimise potential treatment costs and lower milk output as well as labour (e.g., by spending less time monitoring animals by eye). One farmer having used the camera mentioned how they learned to make better use of their time. They said:

> ‘What it has probably done is made me have more use of my time, you know, it’s pinpointing things down and getting them fixed.’ (Farmer 8)

They also noted the benefit of not having to move cows to score them, which enhances productivity and welfare:

> 'The less you can move the cows you'll find the better yield is because (…) the less you're moving them, the less you're upsetting their natural behaviour and therefore it's probably helping drive milk yield.' (Farmer 8)

Others mentioned how the system could help farmers 'do a better job' by being more proactive and better organised. One of them said:

> 'The camera has great benefits because it's picking up differences over a certain period of time (…) so we'll be able to see any changes before the human eye can; we'll be picking things up more proactively.' (Farmer 3)

In turn, this could help improve performance through better animal health and welfare. As one farmer said:

> 'The technology can tell us that she's going lame before you can visibly see it (…) in order for us to treat the animal promptly and hopefully prevent a problem from going considerably worse.' (Farmer 1)

A farmer that was able to use the camera also noted the advantage of being less able to ignore cows that were slightly lame, which they would sometimes do in the past:

> 'I think the biggest change using the camera is (…) pulling out those cows that aren't lame but need a trim. Sometimes it was easy to put off like, you might notice she's got long feet but she's not too bad, she'll do. But I think the fact that it's actually physically on our computer (…) you probably think, alright, it's on paper (…) I really ought to be getting that done.' (Farmer 8)

Similarly, another farmer using the camera mentioned looking at slightly lame cows more attentively:

> 'You do look harder at them. If it's flashing up as a problem or as slightly lame, then you concentrate harder on that one.' (Farmer 2)

In case study B, the use of the application was also seen as a possible way to improve performance on farms by being able to link data on emotional expressivity to other welfare metrics, facilitating a better understanding of where improvements might be needed or possible. For example, links might be made with animal performance, encouraging farmers to adapt management of their farm (e.g., by improving the animals' environments). A participant involved in the pig supply chain said:

> 'We could see patterns starting to build and if we could then marry that up with a reason (…) you might then be able to (…) work out if there's an issue (…). Then you could start making some changes to increase the welfare and the benefit to those pigs.' (Participant 3)

The application was also seen as a way to gain knowledge about the importance of practices that have the potential to enhance animal welfare, such as grazing or the use of enrichment. As a participant said:

> 'If you come from a farming perspective: actually, I want my cows to be in the best place emotionally as possible, and I have got that evidence from down the road that those cows are in a really good place and they've got the following enrichment opportunities, then perhaps I can adopt those. So, it's an opportunity for education for farmers as well as everybody else.' (Participant 1)

Being able to compare between farms was another mentioned benefit of the application, as it allowed to understand where improvements are possible based on evidence. The application was indeed also considered a useful tool for benchmarking. As a participant said:

> 'Farmers consistently scoring lower than other farms, it might be kind of understanding why that is and what could change; what other farms are doing that's giving them greater scores and improving those systems.' (Participant 2)

Double-loop learning

The possibility to improve monitoring and livestock management strategies was observed in both case studies. They differed, however, in the extent to which participants had learned to question those strategies. A farmer from case study A mentioned how the use of the camera system led them to question the level of welfare on their farm in relation to lameness prevalence, which is an issue we mentioned earlier. On this, they said:

> 'The couple of times that I've been onto the website (…) and thinking, oh, maybe that's more than I expected (…) It has made me think about the welfare of the cows. Is it as good as I think it is? (…) Unfortunately, as farmers, you can get a bit blinkered to your own farm.' (Farmer 9)

However, double-loop learning outcomes in case study A were somewhat limited. When asked about whether the use of the camera had influenced their understanding of animal welfare or their approach to the concept, one user clearly stated not having learned much:

> 'To be fair, no. Lameness is lameness. everyone is aware of what it is and the problems it has. So no, it doesn't change that way.' (Farmer 2)

Another farmer said their perception of welfare didn't change following the use of the system, particularly as they were already conscious of it. They said:

> 'I don't know if it changed my perception around animal welfare because I think it's always been fairly high up on the list (…) especially with lame cows, because public perception-wise, that's the easiest thing to pick on.' (Farmer 8)

In contrast, case study B participants mentioned how the use of the application made them think more actively about animal welfare, particularly in relation to animal emotions. Indeed, the method encouraged users to take the time to observe animals and take a close look at how they expressed themselves, both in relation to other animals and the environment which stimulated users to ask 'why' animals were behaving a certain way. As one of them said:

> 'We're certainly far, far more dialled into watching a behaviour as an expression and not just its natural behaviour or its aggressive behaviour or whatever else. Actually, no, why are they

doing that? What are they feeling in order to be doing that behaviour? (…) What is it that's behind that? So that's the big step change really.' (Participant 15)

On this, another participant added:

'It might give them time to think about 'why are they?', 'what's going on here?' That's why I think the app's got a useful position and a useful time to play in the farmers' day.' (Participant 3)

On taking time to observe animals, a participant also said:

'I think we can almost ignore what the actual outcome is, it's more a means of encouraging the stockman to have a look at his flock.' (Participant 12)

The application also made users think about the animals' perspectives and look at them in different ways. A shift in attitudes and approaches to welfare was observed, with a stronger focus on animals' emotional states, as opposed to a sole focus on physical parameters. One participant explained that they had not considered positive welfare in the past, but that the use of the application led to a change in perspective:

'I didn't necessarily really look at the cows and think how happy they were in their environment and how comfortable they seem (…) but yeah, it's definitely got me looking at them in a different way.' (Participant 13)

The application had the potential to drive change and encourage improvements to work towards positive animal welfare. A participant explained how they experimented with different lighting conditions, positions of enrichment bales and perching in poultry farming, and based their judgement on observing changes in the animals' emotional expressivity. They were then able to advise farmers they were working with to adapt management accordingly. On lighting conditions, they said:

'When I was doing the assessment, I noticed that the behaviour of the birds was affected by light intensity (…). The behaviour of the birds (at the minimum legal requirement of lighting

> intensity – 20 lux) was very different to birds at 30 lux light intensity. So, there is a couple of farms (…) I got them to upgrade their lighting system, and I can see a positive change in the birds' behaviour already.' (Participant 14)

Through developing the application and discussing with other stakeholders, participants also reported getting a wider knowledge and understanding of animal expressivity and differences between species. Making use of a wide range of terms to explain subtle differences, the application was seen as a tool to train farm staff to look at animal emotions. As a pig farmer said:

> 'I think it would be quite a good training way, engaging people to actually look at the pigs as animals (…) Unfortunately, there are farms where they don't have that level of empathy (…), so I think from a training point of view, that would be good.' (Participant 6)

The potential of the application to make users think differently and promote reflection was further emphasised by other participants. One of them, for example, mentioned how the application was about changing producers' mentality. They said:

> 'The biggest benefit that I saw from day one is not about the detail and the data, it's about changing the mentality of the producer to think in terms of the feelings of that animal.' (Participant 15)

Others mentioned how using the application was 'thought provoking', helping focus the mind, promoting the subconscious and making them think outside the box. One of them mentioned how using the method became part of their routine; constantly monitoring animals in their heads whilst doing routine jobs. They said:

> 'It doesn't matter what job you're doing in life; you always need to challenge your thoughts on what you're doing, and there are all those things you can do better. And I think using the app, it challenges your thoughts.' (Participant 14)

The use of DLTs thus had important learning outcomes and promoted changed management practices in both case studies. This ranged from improved strategies to reduce lameness with more efficient monitoring and early treatment in case study A, to changing attitudes to observing animal expressivity in case study B, leading farmers to pause and reflect on *why* animals were behaving in certain ways, and then finding ways to adapt management in order to encourage positive expressivity.

3.5.3. Possible challenges to welfare improvements

Some possible barriers to welfare improvements were identified through the case studies. An important challenge was that of changing farmers' mentality. In case study A, some farmers mentioned not wanting to have a look at the data, as it was telling them something negative. As a farmer said:

> 'You know, as a farmer, if it tells you something that makes you feel a bit depressed i.e., you've got really lame cows. Then you're just a bit like, oh, I don't know if I want to look at it.' (Farmer 9)

Perception of lameness levels is a commonly identified issue in dairy farming, and this was something that one of the system's developers learned during this experience. They said:

> 'I think it's highlighted that farmers are not always very good at perceiving the level of lameness or body condition (…). I think a lot of farmers are perhaps more optimistic of their scores than what's actually going on.' (Developer 2)

Some farmers from case study A also believed the system would add more work, especially where they already had their routines, or when they considered that lameness was not an issue on their farm.

Farmer mentality was seen as a challenge by some participants from case study B, who mentioned that farmers could be sceptical about the application. As one of them said:

> 'Seeing somebody coming in and putting some sliders on a mobile phone and then coming up with an assessment (…) they'd just look at it, thinking, well, I could've told you that, I know what these birds are like.' (Participant 12)

On this, another participant said:

> 'In a way, I have to go into their farm to ask whether their cattle are happy or not. It's almost a little insulting. I would be insulted if somebody came to my house and said, right, I'm gonna get this app on my phone and I'm gonna determine whether your dogs are happy or not.' (Participant 10)

Other participants also struggled with the qualitative nature of the method, particularly in the context of animal welfare assessments, which often mostly rely on quantitative criteria. Some participants found it challenging to use terminologies that included terms such as 'happy' or 'depressed' to describe animals and wondered whether this could be interpreted as being anthropomorphic. The lead researcher recognised that making anthropomorphic mistakes is a risk, but emphasised that the use of qualitative descriptors is not per definition anthropomorphic. They said that the value of the method relies on observations made by skilled, experienced assessors, and that rather than imposing mechanistic criteria, the answer to the risks of anthropomorphism is more training. As they said:

> 'There's no point trying to make (the method) more credible by trying to objectify and mechanise and instrumentalise it, which is what so many scientists think is required to make it objective. But you kill it off if you do that.'

3.5.4. Survey results on management practices

Whilst results from the survey do not allow to make inferences on the extent to which PLF technologies may act as boundary objects, they allow to explore the extent to which they may impact farm management and animal health and welfare. This partially helps us to consider what type of learning may have resulted from using the technology. When asked about changes to management routines due to using PLF technologies, 92% of survey respondents indicated making changes to routine tasks, with 52% observing major changes. 83% also observed changes to their work schedule, with a majority observing minor changes (44%) (figure 3.1). Most respondents did not experience changes in terms of numbers of full and part-time staff (77% and 81% respectively). Most, however, experienced changes in the time they spent on digital devices (90%) and with animals (n=63, 82%), with 23% and 27% observing major changes respectively.

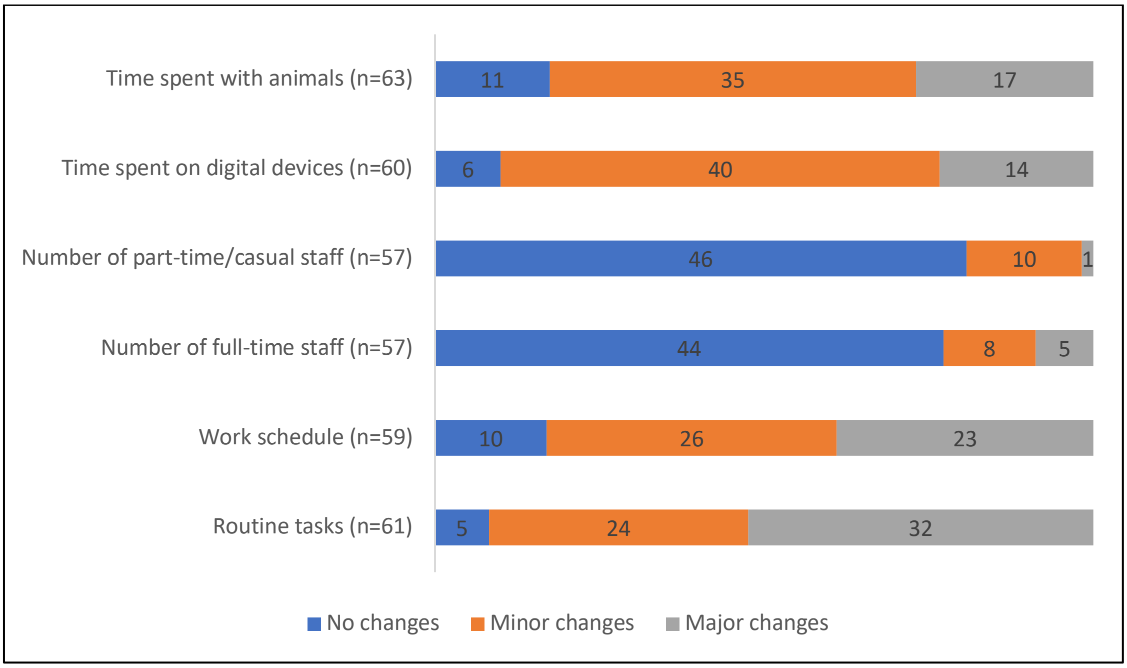

Figure 3.1: Distribution of management changes observed after using PLF technologies

Rating on a Likert scale from 1 (substantially decreased) to 5 (significantly increased), most respondents indicated that the time spent visually or manually assessing animal health and welfare had somewhat decreased (n= 67, Mdn=2, IQR=1). However, most chose not to rely on the data completely; as they manually or visually verified the data collected most of the time (n=66, Mdn=4, IQR=2; on a Likert scale from 1 (never) to 5 (always)).

This decrease did not seem to impact the human-animal relationship (HAR), as, rating on a Likert scale from 1 (substantially decreased) to 5 (significantly increased), most indicated that human contact with cows remained about the same (n=67, Mdn=3, IQR=0), and that the relationship between stockpeople and the herd did not change since using technologies (n=67, Mdn=3, IQR=1). However, 39% of participants did report an improved relationship (6% indicated a much better relationship and 33% a 'somewhat better' relationship).

In terms of impacts on animal welfare, most respondents indicated that the use of PLF technologies had helped make the parameters they were designed to monitor 'somewhat better' e.g., improved heat or lameness detection (n=59, Mdn=4, IQR=1), when rating on a Likert scale ranging from 'much worse' (1) to 'much better' (5). The same was observed when respondents were asked about their perceptions of overall animal welfare levels since implementing PLF, as most indicated that it was somewhat better (n=61, Mdn=4, IQR=1), with 20% of respondents perceiving 'much better' welfare.

Finally, respondents were asked to indicate whether they observed changes in their livestock following the use of PLF based on a list of eight descriptors, using the options 'they are more…', 'they are less…' or 'no change', associated with the following descriptors: 'relaxed', 'calm', 'content', 'friendly', 'nervous', 'indifferent', 'distressed' and 'uneasy' (figure 3.2). The descriptors used in the survey were independent from those used in case study B described above and were inspired by a fixed list of qualitative descriptors that can be found in the Welfare Quality® protocol for Dairy Cattle (Welfare Quality, 2009). Whilst most respondents indicated no change, some indicated that they believed their cows were more relaxed (33%), calm (32%), content (27%), friendly (15%) and that they were less nervous (25%), distressed (23%) or uneasy (23%).

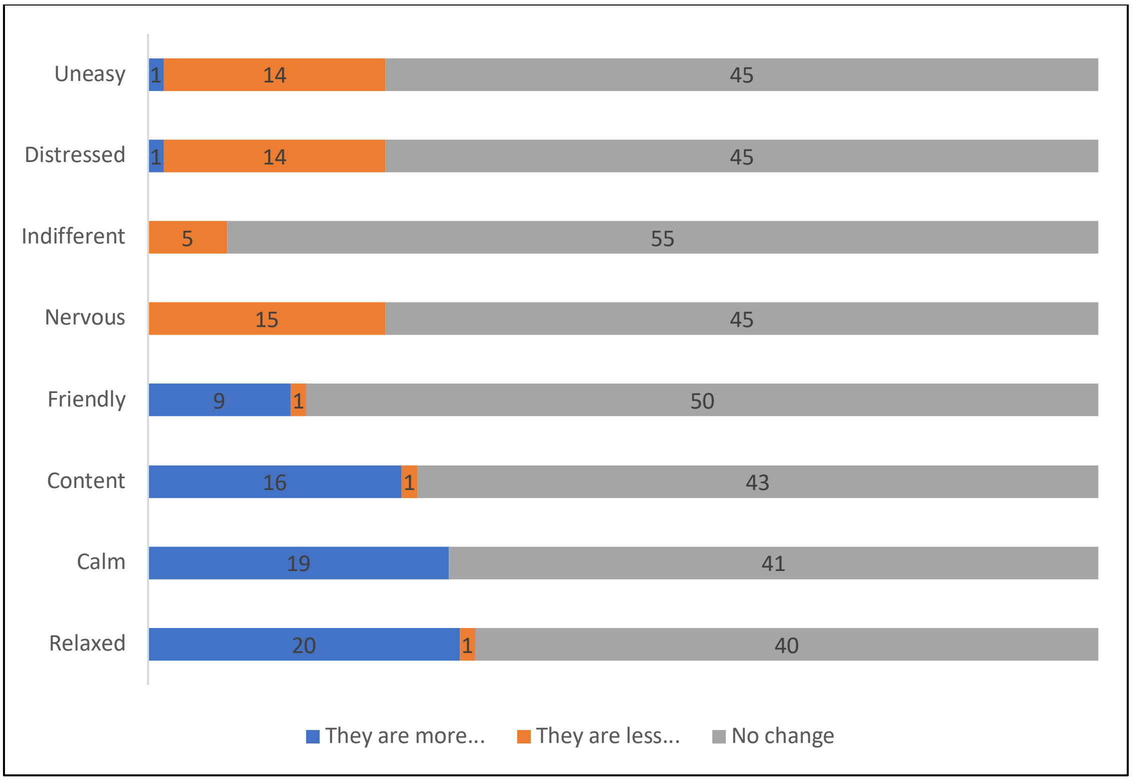

Figure 3.2: Changes observed in animal behaviour inspired by a fixed list of descriptors used in the Welfare Quality® protocol for dairy cattle (2009)

3.6. Discussion

The welfare of farmed animals is highly dependent on human decisions (Boivin et al., 2003), thus the extent to which DLTs may help improve welfare will depend on the way they affect management practices, and whether important aspects of animal welfare (e.g., the HAR and animals' ability to live positive experiences) are considered and improved. Findings from the present case studies indicate that, by acting as boundary objects, DLTs can help inform management by facilitating connections between different actors and fostering learning to improve productivity and better respond to citizens' concerns around sustainability and animal welfare issues. Indeed, the tools could help improve communication and transparency relating to animal health and welfare, or to spot animals whose welfare may be compromised more efficiently.

The technology from case study A, for example, could help farmers be more organised and proactive in relation to lameness, which is an important welfare issue (Whay and Shearer, 2017). In a study conducted on European organic dairy herds, it was found that overall lameness prevalence reached 18%, with some farms reaching 79% (Sjöström et al., 2018). This can be linked to the fact that farmers often underestimate lameness prevalence and the implications for productivity, making it a barrier to reducing lameness prevalence (Leach et al., 2010). Farmers often delay the treatment of less severely lame cows due to limited staff resources, having to balance with other farm priorities, or not understanding the value of prompt, early treatment (Horseman et al., 2014). Thus, the use of a camera could have important welfare implications if it results in the early treatment of lame cows, and a stronger focus on less severe cases as a method of prevention.

Both technologies also had the potential to bridge the gap that exists between consumers and producers. Whilst consumers are more and more concerned about animal welfare and consider that it should be improved, their knowledge of farming systems is limited (Alonso et al., 2020; Sweeney et al., 2022). Consumers often do not look for details; thus, being able to back up welfare claims by providing tangible evidence and increasing trust in farm monitoring practices is important (Frewer et al., 2005). Similarly, being able to demonstrate that positive aspects of animal welfare are considered is particularly relevant, as animals' affective states and ability to live 'naturally' are deemed important aspects by consumers when discussing animal welfare issues (Sweeney et al., 2022). The focus on emotions and more generally, positive animal welfare, is also particularly relevant as it aligns with recent changes in laws relating to animal sentience e.g., *The Animal Welfare (Sentience) Act 2022* in the UK, which recognises that animals experience emotions that deserve consideration.

Most commercially available DLTs currently focus on minimising negative impacts on animal welfare as opposed to promoting positive experiences. This could be due to the lack of evidence regarding the validity of positive welfare indicators and the challenges in measuring them (Schillings, Bennett and Rose, 2021). In addition, farmers tend to be sceptical about the use of animal-based welfare indicators (e.g., the presence of social interactions or play behaviours) and may be reluctant to adapt their systems to increase opportunities for animals to live positive experiences (Vigors and Lawrence, 2019). As Vigors and Lawrence (2019) note, farmers' approach to animal welfare is underpinned, among other things, by their values and preferences. According to a study by te Velde, Aarts and van Woerkum (2002) farmers are not likely to actively seek to increase their knowledge about welfare and are not always aware of the importance of positive welfare aspects such as the ability to display natural behaviour. Thus, it is likely that DLTs that generate a greater understanding of different dimensions of animal welfare, as well as a re-framing of values and beliefs, could lead to more meaningful impacts on management practices and animal welfare than if learning is restricted to improving strategies that are already in place (and potentially fail to address the root causes of existing issues).

In the present case studies, DLTs varied in the extent to which they fostered learning. In case study B, learning outcomes went beyond the re-visiting and improving of existing strategies that characterises single-loop learning; they led to a change in perspective and a re-questioning about what matters for animal welfare, shifting the focus from a mechanistic paradigm to one that primarily views animals as sentient beings – a process characteristic of double-loop learning. Such a perspective aligns with that of the wider public and enables farmers to communicate their process of care – that they spend more time observing their animals and considering why the animals behave in certain ways, and then where possible make improvements in management and housing that encourage positive expressions of emotional well-being (de Weerd and Ison, 2019; Mandel et al., 2016).

The differences in learning outcomes between the DLTs in both case studies may be related to the nature of the discussions they facilitated. In case study B, the use of the application triggered discussions and reflections around broader, emotional dimensions of animal welfare. The qualitative nature of these dimensions allows for greater flexibility in interpretation, as opposed to the more mechanistic data generated by the camera system. The interpretive flexibility of boundary objects indeed facilitates connections between different actors, and the resulting discussions can generate a better understanding of the purpose and use of a tool (Klerkx et al., 2012). In addition, the participative approach to the development of the application (through the generation of the terms used to conduct welfare assessments), allowed the stakeholders involved in case study B to discuss and reflect on the question of animal emotional expressivity, thus facilitating learning around this important dimension of animal welfare. By acting as boundary objects, systems developed participatively encourage social learning between stakeholders, with the level of participation having different impacts on learning (Jakku and Thorburn, 2010; Reed et al., 2016b; Ryschawy et al., 2022). Participation can help bridge gaps between actors that may have different perspectives on a particular issue through discussions and feedback, allowing participants to translate different perspectives and knowledge into more concrete actions (Colnago et al., 2021; Jakku and Thorburn, 2010; van Paassen et al., 2011). This is particularly relevant in the context of animal welfare, as stakeholders' interpretation of this notion can be variable (Vanhonacker et al., 2008). It is therefore likely that DLTs with an interactive component may act as boundary objects and foster double-loop learning to a greater extent. In turn, this re-framing of values may lead to changes in management practices that further enhance farm animal welfare.

Previous studies have used the boundary object concept in agriculture and discussed co-learning opportunities and resulting impacts on farm management (Eastwood et al., 2012; Jakku and Thorburn, 2010; Morris et al., 2020). They have highlighted learning opportunities in promoting understanding of a concept and its values, through increased mutual understanding between actors and guidance in research and analysis (Duru, 2013; Klerkx et al., 2012). To the authors' knowledge, however, the concepts of single- and double-loop learning have not been used in this context in conjunction with that of boundary objects to discuss the possible extent of these objects' impacts. The concepts of single- and double-loop learning (as well as that of triple-loop learning) were used by Reed et al. (2016b) to evaluate farmer learning as a result of participating in Field Labs. They highlighted the challenges in assessing changes in learning and evaluating improvements in farmers' decision making. Combining these concepts may thus be particularly relevant when exploring possible impacts of DLTs on learning about complex issues such as that of animal welfare, which this study aimed to do. As noted previously, animal welfare is a complex notion that can be understood differently by different people, and its improvement will depend on whether management practices will be adapted accordingly, whilst ensuring that all relevant dimensions of welfare are considered.

How DLTs impact management practices and the resulting effects on animal welfare should, however, be further explored. This includes investigating possible effects on the human-animal relationship, which is another important dimension of animal welfare (Boivin et al., 2003). Despite the promising potential of DLTs, previous studies have raised concerns over their potential to promote, for example, the intensification of livestock farming, or to have a negative impact on the human-animal relationship (HAR) if farmers were to spend less time with their animals as a result of using DLTs (Schillings et al., 2021; Stevenson, 2017; Werkheiser, 2018). In the present study, survey results suggested that whilst DLTs can assist or even replace farmers in certain welfare assessment tasks, farmers may re-direct the time saved by DLTs to other tasks which still involve human-animal interactions. This, in turn, can help improve farmers' perceptions of the HAR and levels of welfare, particularly if those tasks assisted by DLTs were of repetitive or difficult nature. This aligns with a qualitative study by Kling-Eveillard et al. (2020), who found that better working conditions following the use of PLF could lead to improved HAR. Future studies should focus on the extent of these impacts from the animals' perspectives in addition to the farmers', combining both quantitative and qualitative methods.

3.7. Animal welfare implications and conclusion

More sophisticated technologies are being developed with the aim to improve farmers' working conditions as well as animal health and welfare. However, ensuring good animal welfare goes beyond the prevention of pain and illness, and includes different dimensions of welfare such as a good human-animal relationship, the ability to engage in natural behaviour and to live positive experiences. The findings of this study indicate that the impacts of using the latest artificial intelligence-based technology on animal welfare will not necessarily be greater than a simpler smartphone application. Indeed, in this study, the latter triggered deeper reflection and learning among users on important but often neglected aspects of animal welfare. Using the concepts of boundary objects and of single and double-loop learning was a useful way to explore these impacts, by focusing on their ability to promote discussion between stakeholders, and to promote a re-framing of values and beliefs. Although the benefits of smart technologies in terms of minimising negative consequences to animal health and welfare must, of course, not be ignored, this study suggests that evaluating the extent to which DLTs can help enhance farm animal welfare should also focus on their ability to encourage users to address different dimensions of animal welfare, regardless of how technologically advanced they may be.

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CHAPTER 4. Perceptions of farming stakeholders towards automating dairy cattle mobility and body condition scoring in farm assurance schemes

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4.1. Information about the paper

This third manuscript was published in *The International Journal of Animal Biosciences: Elsevier Animal* in May 2023. In the previous chapter, I highlighted through the second manuscript that the extent to which animal welfare may be impacted with DLTs may vary depending on what end-users have learned from using the technologies, and how this may have changed their approaches to farm management practices. This fourth chapter stems from reflections triggered by the results of the workshop I have organised to complement the review that constitutes Chapter 2. These results were published as a short commentary in the CABI Agriculture and Bioscience journal in February 2021 (appendix 2), in which I discussed a range of technical, social, welfare, and consumer challenges associated with the use of DLTs, and in which I highlighted the need to involve relevant stakeholders in technology co-creation. Using a wide range of expertise can help operate DLTs in a way that maximises their potential and lead to meaningful changes in terms of farm management and animal welfare, whilst being able to anticipate potential challenges.

The effective use of DLTs indeed requires an increase in cognitive labour and a paradigm shift in management that makes it unreasonable to assume that implementing DLTs in practice is straightforward (Anderson *et al*., 2014). This requires different stakeholders, including farmers, to be included in early discussions so as to better understand the processes of DLT adoption and implementation (Søraa and Vik, 2021). In this fourth chapter, I explore farmers' and other stakeholders' perceptions of the implementation and use of a digital camera to automate the collection of mobility and body condition scoring data for farm assurance schemes. The potential of DLTs to enhance animal welfare, farm management, and consumer trust in this specific context has been discussed in previous studies, but little is known about stakeholders' perspectives on this topic. In this work, I uncovered perceived benefits and key concerns raised by farmers, technology developers, and farm assurance scheme staff. I suggest ways to mitigate potential consequences, and further emphasise the need to involve end-users (e.g., farmers) and other relevant stakeholders in the participatory development of DLTs.

The following sections of this chapter stem from the third manuscript of this thesis. Modifications have been made to the original, submitted paper, following the reception of the journal reviewers' comments in January 2023.

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4.2. Abstract

Animal welfare standards are used within the food industry to demonstrate efforts in reaching higher welfare on farms. To verify compliance with those standards, inspectors conduct regular on-farm animal welfare assessments. Conducting these welfare assessments can, however, be time-consuming and prone to human bias. The emergence of Digital Livestock Technologies (DLTs) offers new ways of monitoring farm animal welfare and can alleviate some of the challenges related to animal welfare assessments by collecting data automatically and more frequently. Whilst the idea of automating welfare assessments with DLTs is gaining interest, little attention has been paid to farmers' perceptions and the perceived challenges that could prevent successful implementation. This study aims to address this gap by focusing on the trial of a 3D machine learning camera to automate mobility and body condition scoring on 11 dairy cattle farms. Semi-structured, in-depth interviews were conducted with farmers, technology developers and a stakeholder involved in a farm assurance scheme (N=14). Findings suggest that stakeholders perceived important benefits to the use of the camera in this context, from building consumer trust by increasing transparency to improved management efficiency. There was also a potential for greater consistency in data collection and thus for enhanced fairness across the UK dairy sector, particularly on the issue of lameness prevalence. However, stakeholders also raised important concerns, such as a lack of clarity around data ownership, reliability, and use, and the possibility of some farmers being penalised (e.g., if the technology failed to work). Better clarity should thus be given to farmers in relation to data governance and evidence provided in terms of technical performance and accuracy. The findings of this study highlighted the need for more inclusive approaches to ensure farmers' concerns are adequately identified and addressed. These approaches can help minimise negative consequences to farmers and animal welfare, whilst maximising the potential benefits of automating welfare-related data collection.

Keywords: Animal welfare monitoring; Automated data collection; Farm assurance; Dairy farming; Precision Livestock Farming

Implications: This study explored farmers' perceptions of automating mobility and body condition scoring in the context of farm assurance schemes through the use of a digital camera. Farmers highlighted the potential of this type of DLT to help improve transparency, efficiency, and greater consistency in data collection. This, in turn, could help enhance animal welfare through improved management, help build consumer trust in the farming system, and promote fairness across the dairy sector. Concerns were, however, raised regarding the possible mandatory use of DLTs such as the camera, and a lack of clarity regarding data ownership, reliability, and use. The findings highlighted the importance of promoting inclusive approaches; including farmers in early discussions to better inform strategies to maximise the potential of DLTs whilst mitigating risks and negative consequences to farmers, animals, and consumers.

4.3. Introduction

The demand for more information on how food is being produced is growing in developed countries, particularly due to increased concerns about its impacts on human health and the environment, as well as on animal welfare (Bredahl *et al.*, 2001). In the EU, this has led policymakers to consider the importance of labelling schemes that can provide consumers with more detailed information, such as those related to animal welfare standards (European Commission, 2016, 2020). Farm assurance scheme labels can help consumers make better-informed choices and have the potential to give producers a competitive advantage and price premiums, thus encouraging them to adapt their management practices to higher welfare husbandry systems. Specific sets of standards, which usually aim to go beyond minimum legal requirements, are defined by farm assurance schemes and in some cases by food retailers. On-farm assessments are conducted on member farms to ensure that producers adhere to these standards (Main et al., 2001). To conduct these assessments, a variety of farm animal welfare assessment protocols are available, such as those emanating from the Welfare Quality® (WQ®) project.

Whilst some of these assessment protocols offer comprehensive assessments of animal welfare, there are challenges associated with their use, including the time required to conduct them manually. The WQ® protocol for dairy cattle, for example, takes between five to seven hours to complete per farm, depending on herd size (Welfare Quality®, 2009). This makes it challenging for farm assessors to conduct frequent welfare assessments on each farm. Often, farms are assessed no more than once a year, capturing welfare levels at points in time as opposed to reflecting welfare status over the long term. In addition, there are concerns regarding the validity, reliability, and feasibility of the measures, and regarding their sometimes-subjective nature which can impact consistency between assessors (Knierim and Winckler, 2009; Czycholl *et al.*, 2016). Opportunities to shorten the time taken to conduct welfare assessments have been explored (Heath *et al.*, 2014; de Vries *et al.*, 2016; Tuyttens *et al.*, 2021). Whilst these shorter protocols may be considered more practical to undertake, they also have limitations such as being less comprehensive, requiring further validation, or omitting aspects of positive animal welfare.

Other solutions are currently being explored, including the use of Digital Livestock Technologies (DLTs), which range from simple smartphone applications to more sophisticated Precision Livestock Farming (PLF) technologies to collect animal health and welfare-related data (van Erp-van der Kooij and Rutter, 2020; Stygar *et al.*, 2022). A wide range of DLTs exists for various livestock species, such as sensors or boluses that can be used to monitor feed and water intake, activity or location, cameras that can detect lameness and body condition, or microphones to help monitor respiratory diseases (Schillings et al., 2021). By offering continuous, real-time, and automatic data collection, DLTs could replace the need for often laborious, costly, and time-consuming manual welfare assessments (Blokhuis *et al.*, 2010; van Erp-van der Kooij and Rutter, 2020). They could also help reduce the subjectivity associated with manual assessments and help enhance consumer trust in labelling systems by allowing the provision of more detailed information on animal welfare parameters (Fuentes *et al.*, 2022; Ingenbleek and Krampe, 2022; Stygar *et al.*, 2022).

Despite their potential, a recent study showed that out of 19 identified standards for certification in the EU, only one quality scheme enabled the direct use of DLTs (in this case, sensors) to provide information on animal welfare (Stygar *et al.*, 2022). This may be explained by the fact that, despite the optimism in some policy and industry circles about digitalisation on farms (e.g., through the media or policy - Barrett and Rose, 2022), there are several important challenges that relate to implementation. Possible drawbacks of digital agriculture were highlighted by Rose et al. (2022), and include issues relating to data ownership, cybersecurity, data interoperability, power imbalances, food system intensification, and consumer backlash. There is indeed a lack of transparency around data ownership and privacy due to a lack of legal and regulatory framework specifically aimed at agricultural data, thus it is unclear who benefits from the data collected, who owns it, and what is being done with it (Wiseman *et al.*, 2019). In addition, many of these technologies are not appropriately validated (Gómez et al., 2021; Larsen et al., 2021; Stygar et al., 2021). For example, Stygar et al. (2021) found that only 14% of commercially available sensor-based DLTs for dairy cattle had external validation trials available, whilst Larsen et al. (2021) found that only 23% of information technologies developed to monitor the welfare of pigs had been properly validated. In addition to this lack of validation, concerns have also been raised about the vulnerability and potential misuse of the data, as well as the overall legitimacy of the technologies (Neethirajan, 2020; Krampe *et al.*, 2021).

These challenges may represent important barriers to farmers' acceptance of the use of DLTs in the context of farm assurance schemes, as they can influence the trust that farmers have in these technologies and a reluctance of farmers to engage with DLTs and to share their farm data (Wiseman *et al.*, 2019). Limited trust can hinder digitalisation and innovation processes, which in turn can affect trust relations among value chain actors and create uncertainty (Rijswijk *et al.*, 2023). Failure to adequately identify and address these challenges in the specific context of farm assurance schemes could thus hinder their implementation and potential opportunities for improved farm animal welfare and increased consumer trust.

Despite the burgeoning literature on the potential benefits and disbenefits of using DLTs to enhance animal welfare (van Erp-van der Kooij and Rutter, 2020; Schillings, Bennett and Rose, 2021), to our knowledge, there are no studies which explore multi-stakeholder perceptions of using DLTs to automate animal welfare assessments in the context of farm assurance. Furthermore, in a review of the digital transformation in livestock farming with a focus on artificial intelligence, Fuentes et al. (2022) argue that there has been limited research on deployment in real-world scenarios. This study seeks to fill the gap by exploring stakeholders' perceptions of the potential benefits and challenges of using DLTs in the context of farm assurance schemes. In particular, it focuses on the trial of a machine-learning 3D camera for body condition and mobility scoring on dairy cattle farms. The use of DLTs for farm assurance involves stakeholders across the supply chain from farm to fork, including farmers, inspectors, and retailers, each of whom may perceive a different set of advantages and disadvantages that could influence adoption decisions. Ultimately, we identify a series of reasons for optimism or concern regarding the use of the camera for automated welfare-related data collection and reflect on how to learn lessons from discussions of similar issues around the pitfalls of agricultural digitalisation in the wider literature.

4.4. Material and methods

This research uses a case study approach to obtain rich, in-depth, and important insights into stakeholders' perceptions of the use of DLTs in the context of farm assurance schemes. Such an approach helps increase our understanding of the research question and to get a holistic view of a potentially complex issue (Yin, 2011).

Ethical clearance was granted by the University of Reading Research Ethics Committee.

4.4.1. Case study description

Mobility and Body Condition Scoring (BCS) are measures that are often required from farm assurance schemes since they can impact dairy cattle productivity and welfare (Whay and Shearer, 2017). Automating these measures is particularly advantageous for these schemes since the data is usually collected manually, which can be time-consuming and prone to human subjectivity (Silva *et al.*, 2021). The DLT used in this case study was a machine-learning 3D camera that automatically collected mobility data (lameness) and BCS in dairy cattle. The cows were scored each time they passed under the camera, which was usually placed above a race e.g., at the exit of the milking parlour. Real-time data was provided to farmers, who could access these on an online platform. The camera was tested on 11 pilot farms in the UK (10 in England, one in Scotland). Nine of the farms adhered to a farm assurance scheme and were trialling the camera to test the possibility of automating the collection of BCS and mobility data; replacing the current scheme's requirement for quarterly, manual, and independent scoring. Two other farms were recruited by the technology company to test the technology. All pilot farms volunteered to have the camera installed and did not have to pay for its implementation during the trial. No stakeholders involved in our study were incentivised to take part in the interviews.

4.4.2. Semi-structured interviews

In-depth, semi-structured interviews were conducted by the first author using topic guides (see appendix 4 for an example) to obtain a rich account of participants' experiences whilst ensuring that the conversations were steered in a way that would address our research questions. Farmers' contact details were provided by the technology developers. A first round of interviews was conducted with the 11 farmers (farm owners/managers or partners). Discussions revolved around farmers' general attitudes towards the use of DLTs, adoption factors and general challenges. The interviews were conducted between August 2020 and May 2021 for 46 minutes duration on average, using the phone or video conference software (e.g., Microsoft Teams) due to COVID-19 pandemic restrictions. A second round of interviews was conducted using the same platforms, between March 2022 and April 2022. Interviews were held for 53 minutes duration on average. The second round was conducted with nine of the 11 farmers, due to one farmer having sold their cows whilst the project was ongoing, whilst another was not able to install the technology due to a lack of system compatibility. Additionally, two technology developers and a stakeholder working for the farm assurance scheme organisation were interviewed. Difficulties linked to the COVID-19 pandemic and technical challenges encountered by the technology developers meant that at the time of the second round of interviews, only two out of the 11 farmers were able to make use of the DLT. This means that the results of this study mostly related to farmers' perceptions of the issues explored, as opposed to being based on their actual experiences of using the camera (except where specified for those two farmers having used the technology). Stakeholder perceptions of technology use are important to understand, since initial decisions to adopt are largely made by farming stakeholders on the premise of perception, rather than from direct experience of using technologies (Rose et al., 2016). Exploring these perceptions, even if some may arise from a position of lack of knowledge or experience about how the technology works in practice, is important to understand implementation challenges. Whilst a deeper focus on attitudes towards the use of the camera to automate the collection of BCS and mobility data in the context of assurance schemes mainly occurred during the second round of interviews, results from the first round of interviews helped get a better understanding of the context and stakeholders' perceptions.

4.4.3. Qualitative data analysis

All interviews were recorded with a smartphone application or using software recording (e.g., Microsoft Teams). The interviews were transcribed verbatim by the first author, to allow for better familiarisation with the data (Braun and Clarke, 2006). The data were analysed thematically using an inductive approach, with the help of a qualitative data analysis software (NVivo 12) for coding. Data analysis was guided by methods from Braun and Clarke (2006) and Ritchie et al. (2014). Based on the data, a thematic framework was developed with a series of themes and sub-themes covering the main topics discussed during the interviews. The data were then coded into these themes, which led to new themes being created throughout the process. The data were then sorted e.g., each theme was reviewed, which would sometimes lead to the deletion or merging of themes. Data summaries were then produced for each theme to help uncover key elements and underlying dimensions that guided the interpretation of the data.

4.5. Results

Based on the discussions with farmers and other stakeholders, several important benefits of using the camera system to automate mobility and body condition scoring as part of a farm assurance scheme were identified. Stakeholders also reported concerns about the potential implications and possible negative consequences of using the camera in this context. Figure 4.1 provides an overview of the findings which are presented below.

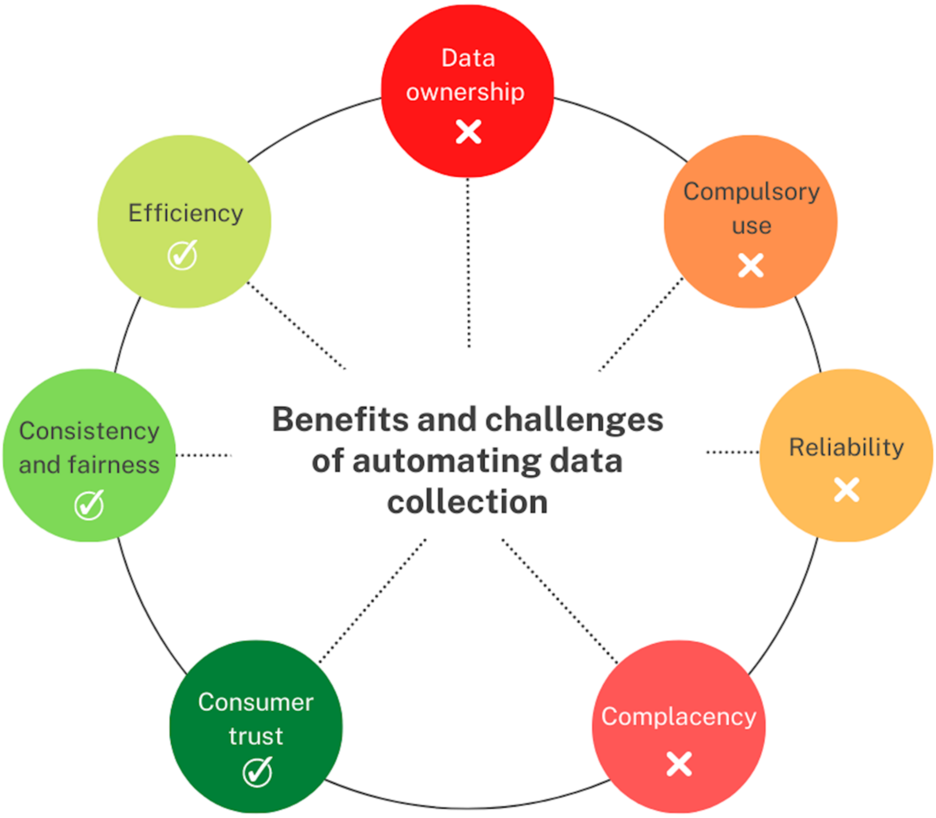

Figure 4.1: Perceived benefits and challenges of automating welfare-related data collection (themes from interviews)

4.5.1. Perceived benefits of automated data collection

Among the benefits of automating welfare-related data collection for farm assurance schemes was the potential for improved animal welfare management through more efficient livestock monitoring. Benefits also included enhanced data consistency, which in turn could have positive impacts on consumer trust and promote fairness across the UK dairy sector.

<u>Improved efficiency and management</u>

The ability to monitor parameters such as lameness and BCS in real time was perceived as a useful way to improve the assurance scheme's efficiency in terms of animal welfare outcomes. Indeed, the camera could help obtain more frequent and precise scoring, which was considered an advantage in comparison to the quarterly snapshots currently obtained by independent mobility scorers as part of the scheme's requirements. According to the assurance scheme worker (AS), this would in turn help farmers be more proactive and allow them to obtain better results thanks to the potential to detect health and welfare compromises at an early stage. As they said:

> 'The argument should be that farmers who are collecting more data in much more detail, more frequently (…) should be able to better, more practically, pick up on any potential mobility issues and then stop severe lameness entering the herd. Whereas, potentially, farmers who are only doing it quarterly won't be able to be as proactive. They might have missed some things and then it's too late, so it should be seen more as a management tool for farmers.' (AS)

One farmer supported this argument by indicating how using the camera could help them manage lameness more efficiently by focusing more, for example, on slightly lame cows. They said:

> 'On the other side, it could be a big step change for our actual individual cow treatment. Currently, we spend a lot of time trying to fix score 2[10] cows and make them go back to being a 1, but maybe we can intervene at that 0 or 1 threshold. I suspect it's a lot easier to get a cow from being a 1 to a 0 than a 2 to a 1.' (Farmer 6)

Similarly, another farmer who was able to make use of the system at the time of the interview mentioned:

> 'I'll probably log in twice a week and just keep an eye on it. I think as a management tool, it's been very good actually. Because we're being pushed a lot more on lameness, with our contract anyway, to try and meet the criteria they want (…). I think it probably helps me just pick some (cows) up slightly earlier than I would have done.' (Farmer 8)

To comply with the scheme's standards, farmers from the case study had to implement quarterly mobility scoring performed by independent mobility scorers. Using the camera to automate data collection was thus seen to save the time and costs associated with hiring independent scorers. As a farmer said:

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[10] The Agriculture and Horticulture Development Board (AHDB) uses mobility scores which range from 0 to 3, with a score 0 meaning 'good mobility', score 1 meaning 'imperfect mobility', score 2 meaning 'impaired mobility' and score 3 meaning 'severely impaired mobility'.

> ‘In the current (scheme) standards, members have to score quarterly (…) so, the thinking is that if we can automate that and (…) spot things before they can be spotted by the human eye (…), not only will it save the farmer time, but also, they'll have a better set of results. I mean, if a cow is going lame, the sooner the animal is treated, the better the outcome. (Farmer 1)

In addition, whilst at the time of the study farmers had to provide the data generated by the camera themselves, one farmer also considered that the possibility of allowing the scheme to have direct access to the data in the future could also be a way to save time. They said:

> ‘If they can get it linked to farm assurance then again, it saves me a job. I'm quite happy with that because you know, we like working with cows. We don't do it because we like playing on computers.’ (Farmer 8)

<u>Improved data consistency and fairness</u>

Obtaining more consistent and accurate data was also a commonly mentioned benefit according to stakeholders, who believed that automating data collection could help remove the subjectivity of manual, human scoring. The subjective element of mobility and body condition scoring can indeed introduce inconsistencies (e.g., results differing between scorers), even where training is standardised. As one developer said:

> ‘The idea of the camera is to take away the necessity for a human to do that scoring and try to automate it and make it more consistent. Because humans have an inherent subjectivity in the way that they assess, they can then end up identifying cows incorrectly, and incorrect actions could be taken as such.’ (Developer 1)

Similarly, on the benefit of the camera to remove human subjectivity, a farmer mentioned:

> ‘The camera doesn’t care whether she’s lame or not, it just says she is or isn’t. I think that’s how our interest has sparked.’ (Farmer 6)

Using the camera was considered more reliable, especially since it is unobtrusive and removes the need for humans to be present, which can cause possible disturbances (cows wanting to 'hide' that they are lame). As the other developer mentioned:

> 'The cows going under the camera are completely unaware of any humans around. So, you get a true picture. If you are scoring, you're always impacting on how the cows score (…) It's (detecting) those cows between (scores) 1 and 2 which are able to mask their mobility a little bit more.' (Developer 2)

This benefit was supported by a farmer who was able to use the camera, who mentioned that lameness on their farm had improved since using the camera:

> 'I always find when you mobility score your cows and there's people around, sometimes they'll walk a bit faster and they can maybe cover up a slight lameness, whereas when they're just going through the camera in the shed, there's no one around. They're just moving along and maybe they're walking more 'true' to how they are. So yeah, I think it has probably improved 'cause I'm finding cows slightly sooner.' (Farmer 8)

The benefit of improved data consistency mentioned above was also closely linked to the opportunity of 'levelling the playing' field across the dairy farming sector, particularly in relation to lameness prevalence and requirements set by milk contracts. Obtaining a more accurate reflection of lameness prevalence and being more consistent across farms was indeed a particularly important point according to farmers. One of them mentioned the pressures put by supermarkets on dairy farmers to keep lameness figures low, which meant that these figures did not always reflect reality. They emphasised the need to have a more robust system to avoid negative consequences. They said:

> 'We don't want to sleepwalk into what (supermarkets) created; they've all done it. All their farmer-scoring information is a work of fiction, isn't it? It's not correct. Farmers, they're not liars, but they're pushed towards not telling the truth.' (Farmer 6)

Whilst the use of the camera was not meant to become a requirement from the assurance scheme at the time of the discussions, a farmer emphasised the possible benefit of making the use of the camera compulsory, to increase fairness in data collection:

> ‘It would be a good thing to make it a requirement because it puts everyone on a level playing field. If you’re all being scored by the same machine, you can’t all go oh, well, he scores harsher than my score or, you know, I think there’s certainly a level of fairness it could bring.’ (Farmer 8)

Similar benefits were also underlined by another farmer, who said:

> ‘The camera has its algorithm and it’s always the same, whereas people are different. So, for the milk buyer, the camera is amazing because it means all the farms will be analysed exactly the same.’ (Farmer 9)

<u>Building consumer trust</u>

Automating data collection was seen as an opportunity for farm assurance schemes to increase transparency and be able to provide evidence of compliance with welfare standards to consumers. Having the data readily available was deemed a helpful way to help farmers and assurance schemes be transparent and protected against potential exposés. As the assurance scheme worker said:

> ‘As a responsible business, we need to have that detail if we are ever challenged on the claims we're making, we want to be transparent and truthful in everything we do. These technologies help us to have that integrity.’ (AS)

Through this increased transparency, an important benefit perceived by stakeholders was also to help build consumers’ trust in the farming system and the confidence they have in farms’ welfare standards. As a farmer mentioned:

> ‘They should have more confidence, shouldn’t they, in the standards that are on these farms. (…) If they're aware that these systems are in place, it's bound to improve their trust in the farming system, isn't it?’ (Farmer 2)

Using technologies like the camera was also considered a way to demonstrate leadership in farm assurance schemes to help consumers make better-informed choices i.e., by offering a form of guarantee that the products they are buying come from animals that have been raised according to the schemes' set welfare standards. As one farmer added:

> 'We're looking to improve outcome measures because the consumer wants healthier cows and wants to be secure in the knowledge that what she or he is buying comes from cows that are well looked after.' (Farmer 1)

Farmers also saw an opportunity to be able to reassure consumers about lameness levels in dairy cows, which they believed was an aspect the public was concerned about. One of them said:

> 'I think that lameness is definitely a biggie at the minute for the consumers (…) So I would suggest to try and make the consumer aware of what we're doing and reassure them that we were doing as much as we can on farm (…) the camera has potentially got a huge part to play.' (Farmer 5)

One farmer also mentioned the potential of DLTs in general to facilitate consumer engagement, using tools they could more easily relate to and understand, such as the use of neck collars to measure activity which has similarities with human fitness trackers (e.g., *Fitbits*).

4.5.2. Perceived challenges of automated data collection

Whilst stakeholders identified several benefits of using the camera in the context of farm assurance schemes, there was also a level of uncertainty among farmers regarding the possible implications. There were indeed concerns about a lack of clarity on data ownership, reliability, and use, as well as about possible impacts on farmers and animal welfare.

<u>Data ownership</u>

At the time of the study, farmers were providing the data generated by the camera to the assurance scheme themselves, as opposed to the scheme having direct access. Whilst some farmers mentioned not having a problem if the scheme did have direct access (one of them stated they had 'nothing to hide', and another mentioned the benefit of it saving them from inputting data), others saw a potential risk. A technology developer emphasised the importance of giving farmers control over data sharing (e.g., with milk buyers). They were concerned that farmers would become suspicious of what is being done with the data and have a feeling of being watched. They said:

> ‘There is a danger if people just see it as an assurance tool (…) because it then looks a bit like Big Brother. They know that (the assurance scheme) is sort of looking and it could be seen as counterproductive. (...) Farmers would then become suspicious that (the assurance scheme) can see what’s going on or the milk buyer. Then, there’s no manipulation, there’s no hiding from that.’ (Developer 2)

Some farmers were also unsure about the schemes’ future intentions regarding data access. They said:

> ‘I don’t know. I’m not sure what the plan is. I mean, from a farmer’s point of view, they would prefer to provide the data to them rather than them being able to have access all the time.’ (Farmer 9)

Another farmer confirmed this point and emphasised the need for the data to remain theirs. They mentioned they would feel ‘very uncomfortable’ if third parties had direct access to the data, especially if there were risks that the technology could be faulty. They said:

> ‘It would be so unnerving if that was the case. If your camera was malfunctioning and suddenly it said you had 400 score threes (…) you might have a policeman knocking on your door and it was the camera that was faulty.’ (Farmer 4)

The same farmer also added the potential impacts it could have on farmers:

> ‘For a dairy farmer in particular, it’s really traumatic if somebody comes on farm and tells them they’re not doing a good job (…) It’s a very difficult thing to have to tell somebody if it’s true, and it’s also a very difficult thing to hear. So, any statutory recording or uploading of this information would be along those lines and would be so sensitive that it just could not be happening.’

Compulsory use

Whilst some farmers saw potential in increasing fairness through improved consistency by automating lameness and BCS data collection, attaining such consistency is likely to be possible only if the use of the camera was made compulsory (e.g., to ensure all farms would be scored the same way). However, requiring the use of the camera would be a particular challenge, as farmers had mixed feelings about this possibility (e.g., see previous section on 'fairness'). One farmer, for example, mentioned how they would not like to be 'forced' to implement DLTs and to share even more data than they are already sharing. They said:

> 'I mean, we're forced to share data with our milk buyer, you know, loads of data. (…) If it is made compulsory for everybody, well, how is that going to work? You know, in general, people are not that keen on being forced to do things. It's always better to make the decision.' (Farmer 9)

Another issue related to a potential requirement to use the camera was that of cost, which is a common barrier to technology adoption. In general, DLTs represent big investments for farmers and can be hard to justify depending on the size of the farms. Making the use of the camera compulsory could thus be a disadvantage for some. As one farmer said:

> 'I think there's certainly a level of fairness it could bring. But (…) to buy that machine these days, it's a significant investment. Especially on the smaller herds, it's probably quite hard to justify at the moment because (…) if you have 1000 cows and you make a 6000 pounds investment, it's only 6 pounds a cow. But if you got 100 cows, it's 60.' (Farmer 10)

In this case study, there were no plans of making the use of the camera a requirement since the scheme was outcomes-driven and wanted to let farmers decide how they achieve those outcomes. However, not requiring the use of the technology also introduced the possibility of penalising some farmers over others, if some were to use automated data collection whilst others would provide data manually. As one farmer said:

> 'If it's not a requirement for everybody to have it, then yes, you have the worry that you're going to be penalised compared to somebody else because of different methods of data gathering, I guess.' (Farmer 9)

Data reliability

Doubts were also raised regarding whom the technology was aimed at benefiting. Indeed, one farmer mentioned that whilst the tool was useful to pick up lame cows, it could also penalise farmers who may not be able to sell their milk if their numbers fall outside of the schemes' deemed appropriate range. This is particularly true if the system lacks accuracy, highlighting the importance of building farmers' trust in the technology (e.g., through adequate validation). One farmer mentioned how inadequate scoring by the camera at the start of the project impacted their trust in the technology, and thus in the possibility of using it to provide data to milk buyers. They said:

> 'I wasn't convinced when it was first actually working and things. It was very, very harsh scoring. It was saying half my herd was lame, and I was thinking well, you know, no one was ever going to use this technology. They may use it for management, but they're never gonna use it for the milk contract because it's gonna make you look terrible.' (Farmer 10)

Complacency

Another risk of automating lameness and BCS data collection highlighted by some stakeholders was that of potentially neglecting the important value that the technology may have in terms of improving animal health and welfare management. As one of the technology developers mentioned, there was a risk that farmers would not get the real value out of the system if they only considered it as a way to save time. They said:

> 'The value of the data, really, is preventative. You know, preventative lameness or preventative body condition score loss. I think, if people are just buying it and it just saves them doing manual scoring then, it's a part of the tool, but it's not the important part. That's the danger.' (Developer 2)

Similarly, a farmer also raised concerns about the risk of becoming complacent about lameness, making farmers pay less attention to mobility. They mentioned the possibility of farmers relying on the data indicating whether they fall into the appropriate range as defined by the assurance scheme, as opposed to focusing on how lameness may impact the welfare of their herd. On this, they said:

'It could be the risk of, you think, oh, my mobility scoring is quite good, I don't need to look at it as much. Maybe there's a risk of you being too relaxed about it (…) you could become complacent having it there.' (Farmer 10)

4.6. Discussion

This study investigated farmers' and other stakeholders' perceptions of the use of a digital camera to automate mobility and body condition scoring in the context of farm assurance schemes. Though there is general discussion of the potential benefits and disbenefits of DLTs on animal welfare in the wider literature (van Erp-van der Kooij and Rutter, 2020; Schillings, Bennett and Rose, 2021), research into stakeholder perceptions of automating aspects of animal welfare assessments is much more limited. This is, in part, because most academic research into the application of technologies such as artificial intelligence (AI) does not focus on practical real-world applications on-farm (Fuentes *et al.*, 2022). In the context of using a digital camera to automate mobility and body condition scoring, which are important animal welfare indicators and are often measured as part of welfare assessments (Roche *et al.*, 2009; Whay and Shearer, 2017), there were perceived benefits and risks. Reflecting on our findings and the contribution of this study in the context of existing literature, we focus the discussion on four broad interlinking themes – data ownership and use, agency, efficiency, and consumer trust. A key overarching point highlighted in the wider literature on farm digitalisation (see e.g., Klerkx, Jakku and Labarthe, 2019; Fielke et al., 2022), and reinforced in this study, is the double-edged potential of digital farm technologies. In our study, impacts could be positive or negative depending on how DLTs are implemented and used in the context of automating aspects of animal welfare assessments, and we seek to integrate this dichotomy throughout the following paragraphs.

Data ownership, consistency, and fairness

Stakeholders in our study discussed several issues related to the data captured by the camera. Positive sentiments concerned the potential ability of the camera to ensure consistency of the data collected, reducing the subjectivity associated with human inspections. Farmers especially thought that improved data consistency would increase the fairness of data collection processes (i.e., collection of BCS and mobility data), ultimately rewarding their positive management activities. Farmers had highlighted the possible discrepancies between reported and actual lameness prevalence in the UK, particularly considering the significant pressure they can find themselves under. It is known that farmers tend to underestimate lameness levels, and the subjective nature of such measures means that differences in assessments can subsist between different mobility scorers, especially when assessing slightly lame cows (Winckler and Willen, 2001; Leach *et al.*, 2010). However, farmers expressed conflicting concerns that the data collected may not always be reliable and thus the camera could unjustly penalise farmers. Additionally, the idea of the data being directly accessible to third parties was a concern to some farmers, who were worried about potential repercussions if the system was faulty.

Stakeholder concerns over the reliability and ownership of data collected by digital farm tools have been expressed in numerous studies interrogating the 'promises of precision' (Carolan, 2018; Rotz *et al.*, 2019; Kuch, Kearnes and Gulson, 2020; Forney and Epiney, 2022), though not specifically in the context of automating welfare assessments. Wiseman et al. (2019) undertook a survey focused on data ownership of 1,000 Australian farmers from a variety of sectors, including livestock enterprises. More than half of these respondents had little trust in technology providers maintaining data privacy or not sharing it with third parties. Just 9% said they had a good understanding of terms and conditions regarding data ownership. In a different survey of 880 Australian broadacre farmers, only 34% regarded themselves as the primary beneficiary of data collection (Zhang *et al.*, 2021). Of most relevance to our study, a survey of 1,500 livestock farmers in Wisconsin around the adoption of digital technology identified farmer concerns over data privacy and security as one of the most significant barriers (Drewry *et al.*, 2019). Similar views shared by grain farmers in Australia led Jakku et al. (2019, p.7) to pose a question on behalf of farmers: 'If they don't tell us what they do with it, why would we trust them?'. Some scholars have even wondered whether increased data capture is being used to increase corporate control over farm decision-making (Brooks, 2021; Forney and Epiney, 2022).

Since we have only begun to capture stakeholder concerns over the use of data collected in the context of farm assurance, little research has been conducted to identify mitigation measures. It may be useful, therefore, to look at proposed solutions to data privacy and security being proposed across digital livestock supply chains. For example, Blagoev and Atanasova (2022) identify blockchain as a technology to keep digital livestock data safe, whereas Abbasi, Rydberg and Altmann (2022) developed a distributed ledger technology to ensure verifiability, traceability, and secure data sharing in a beef supply chain. Solutions should ideally be co-developed with stakeholders across the supply chain to build trust and ensure that their concerns are properly addressed (Rijswijk *et al.*, 2023).

Agency

Automating welfare assessments as part of an assurance scheme may be voluntary or imposed by a retailer or other organisation. Whilst, in this case, the assurance scheme did not intend to make the use of the camera a requirement, stakeholders in our study expressed conflicting views on whether the use of the camera ought to be made compulsory in the future. On the one hand, farmers thought that compulsory adoption would 'level the playing field', ensuring that all farms were being held to the same standards. However, concerns over cost implications and the lack of control over both the decision to impose requirements and the subsequent operation of the camera were also raised. Therefore, if the use of DLTs were to become a requirement, there are two key issues to consider: cost implications and impact on farmer autonomy. To guide the possible response to the conundrum of whether or not to impose the use of DLTs to automate assessment, lessons from the wider literature could be taken up. Though these lessons are not specifically generated in the context of automating welfare assessments, several studies have explored the issue in relation to the adoption of other DLTs. In a study conducted by Lima et al. (2018) on the use of EID tags in sheep farming, it was found that external pressure to adopt technologies negatively impacted adoption and farmers' trust in technologies, and farmers were more likely to consider technologies as an extra burden. The study highlighted that without general approval by the sheep industry, making the use of technologies a legal requirement could exacerbate negative perceptions towards their use and increase feelings of pressure among farmers (e.g., external pressure from the government). Another study on the use of EID tags also highlighted that cost could represent an important barrier to requiring the use of DLTs (Kaler and Ruston, 2019).

An overall message from our study and other research is, therefore, that potential intentions to automate animal welfare assessments through the compulsory use of technology should be planned carefully; ideally involving users from the outset, ensuring that their voices are heard, and providing support to those who are least able to adopt due to cost restrictions (and other factors e.g., lack of digital skills).

Efficiency

Our study considered the use of a specific DLT in the context of automating welfare assessments, which is worthy of closer scrutiny on the subject of efficiency. Existing literature suggests that the primary motivation for considering DLTs as a useful way of performing automated welfare assessments is the potential to shorten the time taken to conduct welfare assessments and to replace subjective manual evaluations (Stygar *et al.*, 2022). A recent review argued that 'the potential to develop ITs [information technologies] for welfare assessment is high' (Larsen et al., 2021, p.17). However, many of the potentially useful technologies are not appropriately validated (Gómez *et al.*, 2021; Larsen, Wang and Norton, 2021; Stygar *et al.*, 2021; Fuentes *et al.*, 2022). Stakeholders in our study agreed with both points; that the camera offered the potential to reduce the time and costs of hiring human experts who may provide more subjective welfare assessments than the camera, but only if it performed accurately.

Negative consequences on animal welfare could also be observed if assessments are based on potentially flawed data, as this may lead to poor management decisions. Whilst one of the perceived benefits of the camera was the potential to provide farmers with more frequent and precise information on lameness prevalence and body condition scoring, improvements to animal welfare still depend on how farmers decide to make use of that information. Whilst some farmers may become more proactive e.g., in lameness management (as observed in this study), concerns were expressed regarding the potential of farmers becoming complacent towards lameness if the technology was used more as an assurance tool and to tick boxes, as opposed to informing management to minimise welfare issues on farms.

In addition, like the camera used in the case study, most currently available technologies are focused on animal health and productivity parameters, as opposed to helping promote positive aspects of welfare (Schillings et al., 2021). As DLTs have not currently been widely applied in practice, the impacts of the use of DLTs on animal welfare are still unclear (Dawkins, 2021). Care should thus be taken in ensuring that this focus on health and productivity parameters should not come to define animal welfare (Buller *et al.,* 2020). Historically, the focus of animal welfare has often been on reducing negative experiences such as pain or stress, though animal welfare scientists increasingly promote the need to consider the importance of positive affective states (Boissy *et al.*, 2007; Lawrence, Vigors and Sandøe, 2019).

Overall, if automated technology was ever to be used as a way to determine levels of welfare on farms, it is crucial to validate whether DLTs offer more accurate results than manual scoring; especially as technologies and associated algorithms are developed by humans and may or may not always involve other relevant experts (e.g., animal scientists) in development. It is also important to understand what impact DLTs will have on farm management and animal welfare on the farm. This will require research which observes and measures on the ground how DLTs are used on farms, including how stakeholders (e.g., farmers, assurance scheme workers, retailers) act on the data and what impact this has on animal welfare.

Consumer trust

In theory, academics have argued that 'implementing remote sensing, biometrics and AI for livestock health and welfare assessment could have many positive ethical implications and higher acceptability by consumers of different products derived from livestock farming' (Fuentes et al., 2022, p.68). DLTs could feasibly reduce potential scoring subjectivity and help enhance consumer trust in labelling systems by allowing the provision of detailed information on animal welfare parameters (Ingenbleek and Krampe, 2022; Stygar *et al.*, 2022). As long as the technology worked effectively, stakeholders in our study thought that using the camera to automate welfare assessments could enhance consumer trust. Studies have shown that despite labels being the primary source of information about animal-based products, many consumers do not trust them (Vanhonacker *et al.*, 2010; Ingenbleek and Krampe, 2022). In our study, allowing consumers to access relevant welfare-related information collected by the camera was considered a helpful way to improve consumer trust by being able to provide evidence of compliance with animal health and welfare standards and demonstrate efforts that these are being adequately monitored. This, in turn, could help consumers make choices in agreement with their personal values (Hoogland et al., 2007).

Whilst, in this case, stakeholders' perception of likely enhanced consumer trust concurs with similar arguments put forward in the literature, the extent to which trust may be improved, however, remains uncertain. Animal welfare labelling from a consumer perspective is a complex phenomenon, and there are uncertainties as to whether and how the data generated by DLTs could provide reliable and validated information, and how this may reach consumers (Ingenbleek and Krampe, 2022). This highlights the need to further explore consumers' acceptance of DLTs and the possible impacts technologies may have on their behaviour (Krampe *et al.*, 2021), particularly since improvements to animal welfare can be driven by consumer demand (Thorslund *et al.*, 2016)

4.7. Conclusion

Discussions with stakeholders involved in a trial to automate mobility and body condition scoring in the context of farm assurance schemes revealed important perceived benefits. This includes the potential to help build consumer trust by increasing transparency and making welfare-related data readily available, as well as helping farmers manage their livestock more efficiently. By providing more frequent and consistent data, the technology was also considered a way to promote fairness across the dairy industry. However, concerns were raised regarding the possibility of making the use of DLTs in the context of farm assurance schemes compulsory in the future, especially considering the current lack of clarity around data ownership and reliability. Unreliable data could unjustly penalise farmers, especially if the data was made directly accessible to third parties. To promote successful implementation of DLTs in this context, better clarity should thus be provided to farmers in relation to data governance, and adequate support should be provided. Solutions should also be in place to ensure the data generated is adequately validated and evidence provided regarding its accuracy. The study revealed the complexity of DLT implementation in the context of assurance schemes and highlighted the need for more inclusive approaches to innovative processes; including farmers in discussions to better understand their perspectives and identify their concerns. Due to the relatively small number of interviews conducted in this study and the potential bias introduced when involving farmers that volunteered in this specific trial, more research should be undertaken to strengthen our understanding of the potential benefits and barriers to the use of DLTs in farm assurance schemes and provide appropriate guidance to maximise the potential of these technologies whilst mitigating the risks.

Ethical approval

Ethical clearance was granted by the University of Reading Research Ethics Committee.

Data and model availability statement

None of the data were deposited in an official repository for reasons of commercial sensitivity.

Declaration of interest

None

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CHAPTER 5. Managing end-user participation for the adoption of digital livestock technologies: Expectations, performance, relationships, and support

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5.1. Information about the paper

The fourth and last manuscript of this thesis was published in 'The Journal of Agricultural Education and Extension' in March 2023. This paper was presented at the 10th ECPLF & PDC (European Conference on Precision Livestock Farming and International Conference on Precision Dairy Farming) 2022, in Vienna, Austria, which was held from 29th August to 2nd September. In the previous chapters, I have highlighted a variety of factors that can influence animal welfare enhancements with DLTs. This includes DLT's ability to address the positive dimensions of animal welfare and to foster learning about these important dimensions, as well as the challenges related to DLT implementation. These papers have highlighted the need for a wide range of stakeholders to collaborate at the early stages of technology development, to better identify end-users' needs and priorities, whilst being able to anticipate and mitigate negative consequences.

Whilst participation is often regarded as a key solution to promote technology uptake, managing these processes is often challenging. Some of these challenges have previously been discussed in the literature, but less is known about how these challenges can affect stakeholders' engagement and attitudes towards the use of DLTs. In this fourth and last paper, I reveal how, despite the many benefits of participation, challenges met during participation can also create frustration and impact end-users' motivation to use DLTs. Through this study, I show that participatory processes do not straightforwardly encourage DLT uptake and suggest key considerations to optimise participatory approaches.

The following sections of this chapter stem from the fourth and last manuscript of this thesis. Only minor modifications have been made to the original, submitted paper, including formatting changes to ensure consistency in the thesis (e.g., table and figure numbers).

5.2. Abstract

Purpose

End-user participation is often encouraged to promote the uptake of Digital Livestock Technologies (DLTs). However, managing participation during DLT development can be challenging. We explore how participation decisions can impact end-users' engagement and attitudes towards the process, and suggest strategies for improved management.

Methodology

We explored the experiences of end-users (e.g., farmers and farm assessors) and other stakeholders (e.g., developers, researchers, industry) involved in the development and testing of DLTs on UK farms, using semi-structured, in-depth interviews (N=31).

Findings

Participation can help develop technologies that better align with users' needs, promote learning, and encourage feelings of ownership. However, participation can be a double-edged sword. Inadequate levels of involvement, management of stakeholder relationships and expectations, and available support can negatively impact end-users' engagement and attitudes.

Practical implications

Our study highlights the importance of understanding how management decisions during the participatory development of DLTs can influence the engagement and attitudes of end-users towards the process.

Theoretical Implications

The study contributes to the participation literature in agriculture and demonstrates the importance of using a critical lens to avoid making normative assumptions that participation necessarily promotes uptake in a linear, uncomplicated fashion.

Originality/Value

Participation is seen as key for technology adoption. However, the potential downsides of participation have received less attention in relation to the engagement of end-users in the process.

Keywords: Digital Livestock Technologies; Participation; Precision Livestock Farming; Stakeholder engagement; Technology adoption; Livestock monitoring.

Paper Type: Research paper

5.3. Introduction

As global population grows, so does global meat and dairy consumption (OECD/FAO, 2021). Alongside this challenge is the growing concern over animal welfare, as consumers increasingly care about the ways in which production animals are raised (Alonso, González-Montaña and Lomillos, 2020). However, meeting the needs of increasing numbers of animals is becoming more challenging as the number of farmers declines. The potential of Digital Livestock Technologies (DLTs) is therefore increasingly highlighted, as they are designed to help farmers improve livestock management. DLTs include a wide range of technologies, from smartphone applications to more sophisticated Precision Livestock Farming (PLF) technologies which allow the continuous, automatic and real-time monitoring of animals (Berckmans, 2014). This includes heat or disease detection, monitoring feeding behaviour and animal location using sensors, cameras or even sound-based systems (Schillings, Bennett and Rose, 2021b). Farmers can track changes in conditions or behaviour, allowing them to make timely decisions, thus improving productivity, animal health and welfare, whilst limiting financial losses.

Studies suggest, however, that the adoption of DLTs is currently low in many places (Gargiulo et al., 2018; Silvi et al., 2021). Adoption rates depend on different factors such as farm type, herd size, husbandry system or farmers' age, education, and IT skills (Pierpaoli *et al.*, 2013; Gargiulo *et al.*, 2018; Groher, Heitkämper and Umstätter, 2020). Adoption factors also include cost, performance, a lack of awareness about existing technologies, or data privacy and interpretation (Borchers and Bewley, 2015; Drewry *et al.*, 2019; Silvi *et al.*, 2021). In addition, many DLTs still lack accuracy and validation (Gómez *et al.*, 2021; Larsen, Wang and Norton, 2021; Stygar *et al.*, 2021), which can affect farmers' trust and attitudes toward them (Schillings, Bennett and Rose, 2021a). Although factors influencing adoption have been widely studied in the agricultural sector, less attention has been paid to the ways farmers, adapt to, and make use of these technologies (Eastwood, Chapman and Paine, 2012; Rose et al., 2016).

Several models and concepts have been used to explain the process of technology adoption by farmers, each identifying a range of farmer-centric, technology-centric, and wider socio-political environment factors influencing adoption. These include the Technology Acceptance Model (see Pierpaoli et al., 2013), the Triggering Change Model (Kvam, Hårstad and Stræte, 2022), Normalisation Process Theory (Kaler and Ruston, 2019), and 'user readiness' (McCampbell *et al.*, 2021). In their study, Rose et al. (2016) adapted the Unified Theory of Acceptance and Use of Technology (Venkatesh *et al.*, 2003) to the use of decision support tools in agriculture. They gathered the core factors that influence behavioural intentions such as relevance to users, ease of use, and performance, which were found to be affected by modifying factors such as age or IT skills. Moreover, facilitating conditions (e.g., integration into farmers' workflows) and driving factors (e.g., satisfying legislative or market requirements) were found to directly influence uptake and use. These different factors highlight the importance of identifying farmers' needs and adaptation challenges, particularly considering the complexity of some technologies.

Many systems are based on what developers consider priorities, focusing on a specific area as a result of a 'technology push', meaning they are not always adapted to farmers' needs (Lindblom *et al.*, 2017). A lack of alignment with their expectations can cause them to ignore the technology, even after it has been installed on-farm (Rotz *et al.*, 2019). To avoid developing inappropriate technologies, adopting a co-design or farmer-centred approach is increasingly encouraged (Kaler and Ruston, 2019; Eastwood, Turner and Romera, 2022). We note that there is a vast literature on user participation in technology development across sectors and topic areas; here we build on previous studies that focus on user participation in digital livestock technology design and implementation. From the wider literature, we know that there is a wide spectrum of participation; from extensive involvement of end-users in processes of co-production and co-design, where users can shape projects and contribute to knowledge, to much less involvement where users are merely informed about or coerced into actions (see e.g., Arnstein, 1969; Reed, 2008; Bell and Reed, 2021). The same is true in agriculture where farmers or other end-users (e.g. vets, agronomists) can be involved from the early stages of technology development or at a downstream stage in prototyping, on-farm testing, or even at the point of scaling (Kenny and Regan, 2021; Eastwood, Turner and Romera, 2022).

Participatory approaches can help better identify farmers' needs, reduce the risks of overlooking the issues that farmers want to address, and ensure that their tacit knowledge is incorporated (Eastwood, Chapman and Paine, 2012; Ingram, 2014). This can lead to improved technologies, social learning, the development of a sense of shared ownership, positive changes in perceptions towards decision tools, and increased adoption and adaptation (Jakku and Thorburn, 2010;

Hennessy and Heanue, 2012; Valls-Donderis et al., 2014). Cooperation and communication with farmers are crucial for the success of innovation systems, particularly during the testing and validation phases, where farmers act as 'beta testers' (Busse *et al.*, 2015). Thus, participation can make a direct contribution to the key factors influencing technology adoption by farmers (Rose et al., 2016).

More participation does not, however, necessarily mean better outcomes (Hoffmann, Probst and Christinck, 2007; Neef and Neubert, 2011). There are several challenges in doing participation, including managing conflicts, identifying appropriate stakeholders, and building trust (see Reed, 2008). Strategies for participation include accepting the differences between farmers and developers in terms of epistemologies. Their tacit knowledge is crucial in understanding their engagement with technologies and should be considered and made explicit (Hoffmann, Probst and Christinck, 2007; Higgins *et al.*, 2017). It also means building trust by ensuring that projects are sufficiently flexible and that developers understand farmers' priorities (Bruges and Smith, 2007). In turn, this can help maintain farmers' commitment and enthusiasm for a project.

Other challenges of participatory development can be found: they can be costly, time-consuming, and slow down development (Kerselaers *et al.*, 2015). The ability of different stakeholders to adapt to different opinions, aligning diverging interests and considering the degree to which actors are involved can be particularly difficult in co-producing innovation (Klerkx and Nettle, 2013). While restricting stakeholders to discussing technical aspects and logistics may limit success, a balance must also be found in terms of the frequency and nature of interactions between stakeholders to avoid 'participation fatigue' (Neef and Neubert, 2011).

Building on previous studies, we use two case studies to explore how participatory processes can influence the engagement and attitudes of end-users towards digital livestock technologies. We critically evaluate how the process of participation can be managed appropriately to overcome potential pitfalls and use a critical lens from the outset to avoid making normative assumptions that participation necessarily improves adoption outcomes in a linear, uncomplicated fashion. Though our case studies focus on DLTs, our recommendations on how to manage end-user participation are likely to be applicable to the development of other technologies across the agricultural sector.

5.4. Material and methods

A qualitative approach was used to obtain rich data on end-user experiences within the context of the two case studies. Case studies allow the in-depth exploration of complex phenomena that occur in real-life settings (Crowe *et al.*, 2011). Here, the aim was to understand how end-user participation can affect attitudes and engagement in participation processes. In our case studies, end-users were farmers (Case Study A) and farm assessors (Case Study B) and we also included perspectives from developers, retailers, and researchers involved. Ethical clearance was granted by the University of Reading Research Ethics Committee.

5.4.1. Case study descriptions

Case study A: Cattle mobility and Body Condition Scoring

Body Condition Scoring (BCS) and mobility scoring (MS) are measures that are often included in cattle welfare standards due to their impacts on productivity and animal welfare. These measures are usually taken by humans, introducing possible biases and errors. Automating these measures can help reduce these risks while obtaining a regular feed of information. Thus, a digital, vision-based system to monitor BCS and MS in dairy cattle was developed by a private technology company and tested on 11 farms in the UK. Nine of them volunteered to test the system as part of a farm assurance programme that had an interest in automating this data collection, whilst two others were brought on board by the technology company to test the technology. The system scores the cows each time they pass under the camera, which is placed above a race (usually as they exit the milking parlour). This provides real-time data which can be accessed online by participating farmers. All pilot farms volunteered to have the camera installed and did not have to pay for its installation.

Case study B: Smartphone application

A smartphone application was developed by a UK research institute for the assessment of emotional expressivity and well-being in farmed animals and was licensed by a UK retailer to assist with further development and testing, and enable supply chain staff to assess animals' emotional wellbeing and better manage their quality of life. The application can be applied to different livestock species (including cattle, poultry, pigs, sheep, goats, and salmon), allowing farm assessors from different supply chains to conduct assessments on animals' emotional experiences. Assessments are based on customised descriptive terminologies balanced for positive and negative emotional expressivity that were developed participatively by key stakeholders (including farm assessors, veterinarians, farmers, and others e.g., supply chain directors). These include, for example, terms like ‘playful’, ‘distressed’ or ‘relaxed’. This was guided by the lead researcher who developed the method on which the application was based. After observing the expressive demeanour of animals during farm visits, farm assessors score each descriptor using sliding scales. The application then integrates these scores through multi-variate statistical analysis. This produces a graph locating visited farms in overall patterns of animal emotional well-being. The graph can be used by assessors to make comparisons between farms and to discuss with individual farmers how the emotional well-being of animals on their farms may be managed or improved.

For convenience, we used the terms ‘developers’ to include technology companies and staff (e.g., technicians) involved in technology design and development. The terms ‘stakeholders’ and ‘participants’ are used interchangeably to include all people involved in the case studies, while the terms ‘users’ include those using the technologies (i.e., farmers and farm assessors).

5.4.2. Semi-structured interviews

In-depth, semi-structured interviews were used to obtain detailed accounts of participants’ experiences while ensuring that the discussions addressed our research questions. The interviews were conducted by the first author, using topic guides adapted to each stakeholder (see appendix 4 for an example). Two rounds of in-depth interviews were conducted for case study A. The first round involved the initial 11 farmers and was conducted before they were using the technology. The interviews took place between August 2020 and May 2021 and were held for 46 minutes duration on average, via the phone or using video conference software (e.g., Microsoft Teams) to remain in line with the COVID-19 pandemic restrictions in the UK at the time. Discussions revolved around general attitudes towards DLTs, adoption, and expectations about the trialled technology. Due to compatibility issues, or some farmers having sold their cows during the project, the second round of interviews was conducted with nine of the 11 farmers, in addition to two technology developers and a stakeholder working for a farm assurance scheme organisation involved in the project. To the author's understanding, the technology developers, who were developing the software and hardware, did not have a specific farming background but were involved in farming-related projects for several years. These were held for 53 minutes duration on average, using the same platforms, between March 2022 and April 2022. Discussions revolved around experiences implementing the technology, farmer participation in technology development, communication with stakeholders, and attitudes towards the technology.

The same topics were discussed with the stakeholders involved in the testing of the smartphone application during a single round of interviews held in May 2022. The lead researcher provided contact email addresses for 21 stakeholders of the retailer's supply chains who were involved in trialling the application and who were willing to be contacted by the first author. Of these, 16 stakeholders involved in the testing of the application and covering different species (cattle, swine, poultry and fish) including farmers, farm assessors (some of them were also farmers themselves), supply chain directors and others involved in the project (e.g., coordinators, project managers) agreed to be interviewed. An interview was also conducted with the lead researcher. Interviews (N=17) were conducted using the same platforms as case study A and lasted 50 minutes on average.

Quotes from case study participants were used to support statements in the results and discussion section 3. For case study A, we identified farmers with 'farmer 1' to 'farmer 11', and developers with 'developer 1' and 'developer 2'. Due to the variety of participants in case study B, the different stakeholders were identified with 'participant 1' to 'participant 16' for simplicity.

5.4.3. Qualitative data analysis

The interviews were recorded using a smartphone or software (e.g., Microsoft Teams) recording options. The interviews were transcribed verbatim by the first author, which allowed her to familiarise herself with the data (Braun and Clarke, 2006). The data was then analysed thematically. A qualitative data analysis software (NVivo 12) was used for coding, guided by methods from Braun and Clarke (2006) and Ritchie *et al.* (2014). An initial thematic framework was produced, with themes and sub-themes covering the aims of the study. Data were then coded into these themes, with new themes emerging throughout the process. They were then sorted, and each theme was reviewed, sometimes resulting in the deletion, or merging of themes. Data summaries were then produced for each theme and interview, allowing to draw out key elements and underlying dimensions that guided data interpretation.

5.5. Results

5.5.1. Approaches to participation

Our case studies sit in specific places on the spectrum of participation. In both cases, a prototyping participatory approach was used, whereby end-users were involved in the testing of technologies. Such an approach aims 'to observe user interactions, detect potential failures, and refine the design towards an easy and appealing user experience' (Steinke et al., 2022, 3). While using an advanced prototype means it is difficult for developers to 'backtrack', it also allows exploration of operational aspects, new functionalities and issues to solve (Cerf *et al.*, 2012). Here, both technologies were advanced prototypes, but not finished products. Whilst in case study A, farmers were engaged in the testing phase of the prototype once it was developed (ie. they were not involved in its technical development), case study B participants were involved at an earlier stage of method development, making use of the fact that the application allows users to insert their own customised descriptive terms. The extent to which end-users were involved in the co-production of DLTs thus varied between the case studies. Here, the focus was therefore not to compare both case studies, but rather to understand how these participatory approaches were managed in both cases and the resulting outcomes to allow making practical recommendations.

Case study A

A trial network of farmers was used to test the camera on their farms. Farmers' involvement was an important aspect of technology development according to the farm assurance worker, who said: '[w]e need farmers to be part of innovation projects like we have done; from the start, to help co-develop it.' Technical issues in addition to external challenges such as the COVID-19 pandemic affected developers' ability to visit the farms and delayed the project by several months. Whilst the system was operational for two farmers, others were not able to use the technology. Issues ranged from power and connectivity issues, hardware and software adjustments, compatibility issues and unreliable data; leading technicians to visit the farms on several occasions. During these visits, technicians ensured that farmers' and animals' routines were not interrupted by their presence. This was well received by farmers, who described them as being very professional when out on farms. The need to focus on addressing technical challenges and a lack of resources was, however, seen as a barrier to including farmers in early decisions. As one developer said:

> 'It's very little point in having a whole discussion about what farmers want if we are unable to deliver it.' (Developer 1)

They also added being wary about asking for too many opinions, thinking it could have compromised development:

'You have to be careful; too many cooks spoil the broth. If you have too many people inputting things, you can end up making something that nobody is happy with.' (Developer 1)

Developers were informing farmers and taking feedback individually as they went, such as when out on farms. Farmers mentioned having attended a single meeting since the installation, during which developers gave details about the issues encountered and the steps taken to address them. Farmers were thus not able to share their experiences with others throughout the project.

Initial training opportunities included informal, one-to-one demonstrations of how the data platform worked, although further training was planned once issues were sorted. Some farmers mentioned having experienced poor backup and a lack of communication. One farmer stopped hearing from the company following changes made on the farm. They said:

'It was taken down and then we said, once we get the new exit race complete, you can come back, and we can fit the cameras. But that never happened.' (Farmer 5)

Another farmer mentioned the short notice developers had given them to organise the stakeholder meeting, during which they had been asked for a testimonial despite not being able to use the system. They said '[t]hey were seriously running before they can walk'. (Farmer 6)

Case study B

Participation was also considered a key element by the lead researcher to keep users engaged and to give them a sense of ownership. As the lead researcher said:

'It's very important for me that (the method) is developed and trained participatively, you know, that we work together with the farmers and the staff to develop the particular terms.'

They organised meetings for each supply chain, which included farm assessors, farmers, and other experts such as veterinarians. Participants were shown videos of animals in a variety of environments to generate the descriptive terms they believed best described the animals' emotional expressivity. Following discussions, participants selected and defined lists of approximately 20 descriptive terms per species to be used during the assessments. During these sessions, participants were also invited to provide feedback on the application and make suggestions for improvement. Farm assessors were generally positive about the participation process and were satisfied with the opportunities to provide feedback through regular stakeholder meetings, during which they were also able to keep up to date with developments. They had regular training opportunities, although external barriers such as the COVID-19 pandemic meant that training was undertaken online. Participants were also satisfied with the level of communication with the lead researcher and their ability to guide and support them. However, some mentioned that more direct contact with the application developers to obtain technical support would have been beneficial.

Noting that the level of participation varied between case studies, we discuss the outcomes of participation and how these impacted users‘ engagement and attitudes towards the participatory processes.

5.5.2. Impacts of participation

In both cases, participation had a positive impact on technology design, as it helped make DLTs better aligned with end-users’ needs. There were also positive learning outcomes, although feelings were mixed in case study A. Similarly, participation had varying effects on users’ engagement in the process and on the confidence they had in the systems (both positive and negative effects).

Improved alignment with users’ needs

The differences in terms of farm location, systems, and designs, allowed developers from case study A to gain a breadth of experience that enabled them to make the technology more reliable and applicable to different systems. As a result of user feedback, developers believed they were able to move forward more quickly and better understand the challenges. One developer from case study A said:

> ‘Because everywhere was different, we’re coming up with different problems on different farms, which is exactly what you want; you want something that’s very varied so that you can address all issues as and when they come.’ (Developer 2)

Farmers from case study A emphasised the need for the system to be integrated with other farm management software, which developers had started to implement. As they noted:

> 'It's not so much the technology working, it's how it integrates with everything that you are already doing (…) it has to integrate with our working day.' (Farmer 4)

Involvement of the different stakeholders in the development of the application (B) helped to ensure that the descriptive terms generated were in line with day-to-day observations on-farm and to develop an application that was practical, easy to use and easily integrated. As an assessor said:

> 'Farmers really are experts in their species (…) they're around these animals every single day, (their input) is really valuable to make sure that they we've got terms that work for the species.' (Participant 2)

Stakeholders also had opportunities to suggest new features to the existing design which were discussed with the lead researcher and incorporated by developers. This included a feature allowing the addition of more details to the assessments such as weather conditions, time of the day, and other factors that could have an influence on the assessments.

Learning outcomes

Case study B involved training sessions in which stakeholders were informed about the assessment methodology and its technical representation in the mobile application. Following that, they were invited to discuss their understanding of different livestock species' behavioural and emotional expressions, and the potential relevance of the assessment method for managing animal welfare on their farms. They then selected a set of customised descriptive terms they considered suitable for their particular supply chain and assisted with defining the meaning of each descriptive term. This process generated learning and greater awareness of how and why animals behave in different ways. Working alongside development also helped increase participants' capacity to adapt to the system. One participant said: '[W]hen you're part of the concept, then you understand its application, I suppose.' (Participant 9)

In case study A, feelings around training opportunities were mixed, as while some believed the technology was straightforward enough to understand, others felt that training did not allow them to make the most out of it. They said:

> ‘I mean, it’s not complicated to just click and find stuff I suppose, but there might be a whole lot of things you can do on the website that I have no idea.’ (Farmer 9)

Another farmer was also critical:

> ‘It was like a two-minute whistle-stop tour (…) I knew so little about it; I had no inclination to even try and learn.’ (Farmer 7)

According to developers, however, the technical issues they had encountered, the global pandemic situation, and farmers’ lack of time made it challenging to organise training sessions. Reflecting on this, a developer said:

> ‘I think there's a bit of that hesitancy on our part and farmers are always busy, so you just grab 10 to 15 minutes with them and then they're off to do whatever they were doing before (…) I think there is a need to get everybody together to sort of go through it.’ (Developer 2)

They mentioned that some farmers were experiencing issues with the technology, but due to the distance and travel restrictions caused by the pandemic, it was not always possible to offer support. The same developer said:

> ‘I think we could have dealt with that better. (…) Either pop out and deal with it or speak to them over the phone or do it remotely. I guess with the pandemic and everything, that didn't help with travelling.’ (Developer 2)

User engagement

The importance of end-user engagement was emphasised by several interviewees. A farmer from case study A said:

> ‘You can have all the knowledge in the world, if you can't engage your audience or your customer (…) it's pointless and hopeless. So that might be something for (companies) to understand: how the farmers will perceive their product and will think about it.’ (Farmer 4)

The same farmer discussed the stakeholder meeting during which developers gave information about the development process. They said:

> ‘I didn't appreciate how much work they have done to drive the product forward (…). Having had it explained, I'm now fairly enthusiastic about it.’ (Farmer 4)

A developer of the camera technology (A) felt that participation had helped to build relations with farmers:

> ‘I think it helped build relations because we were there quite often and we were quite slick and we didn't cause them too many problems, I hope.’ (Developer 2)

However, some farmers mentioned being disappointed by the developers’ approach and pointed to a lack of communication and engagement, which impacted some farmers’ motivation and interest in the project:

> ‘I've no idea who they were. The only contact we've ever had was (the technician) who came and installed the camera and fixed the technical problems, which is a strange way to run a trial, isn’t it?’ (Farmer 2)

Some of them mentioned how they felt a lack of interest from developers in farmers’ experiences, which did not encourage them to make use of the technology. As a farmer said, ‘[i]t was just like, well, if they're not looking at it, I'm not looking at it’ (Farmer 7).

This lack of communication also affected another farmer’s attitudes toward developers. Whilst this farmer had an operational system and was satisfied with the technology, this lack of support resulted in them being more likely to invest in the system if it came from another firm.

Some farmers also mentioned the limited opportunities to discuss with other farmers, which also affected their motivation to use the technology. The importance of feedback from peers has been emphasised by a farmer, as it motivates them to make use of it. They said:

> ‘A lot of farmers will take the opinion of other farmers (…) to see how they found it. Often, farmers will have good little hints and tips on how to make the most of it. (…) Then, when it comes on to your farm, you make a big effort to use it’ (Farmer 9)

Participation in the development of the mobile application (B) clearly helped one participant to feel more closely involved with the project team. They said:

> ‘When I was invited to this meeting, I actually laughed. But see, when I started to develop the terms along with (the researcher) and the rest of the team, then I started to get better buy-in.’ (Participant 14)

The ability to decide on the descriptive terms used in the application’s welfare assessments and to provide regular feedback gave participants a sense of ownership and a desire for the technology to be successful. One of them said:

> ‘You feel (…) a slight sense of pride in actually being involved with it and wanting to kind of get it to fruition.’ (Participant 2)

Yet, the fact that the application users generally only had contact with the lead researcher led some to feel distanced from technical support.

Confidence and attitudes towards DLTs

Technical performance during the participatory process was a source of positive and negative impacts. A farmer involved in developing the camera was prepared for glitches and set his expectations accordingly. They said:

> ‘I expected there to be a few problems along the way. I think if (…) it ran for absolutely bang on first time, I would have been very, very surprised (…) So, I think it’s all been pretty good.’ (Farmer 8)

Confidence in technologies and trust in technology developers were important factors which could be influenced during the process of participation. In case study B, the process helped build trust between users and the lead researcher, and towards the approach. One participant said, ‘[t]here was independent, scientific rigour and research behind the process (…) that's really why it appealed' (Participant 15).

Prototyping is a process designed to identify flaws in a system and resolve them. But there is a risk, which is relatively unacknowledged by the literature, that introducing a flawed technology too early can negatively affect user confidence and attitudes towards the technologies. A lack of accuracy and reliability such as when technologies engender too many false positives can impact users' confidence in a system and hence its use. As one farmer said:

> 'If you start crying wolf on a regular basis and it's proven not to be reality, then the confidence just goes (…) Inevitably, human nature means that you stop looking at it and using what it can tell you.' (Farmer 4)

Witnessing the challenges and changes over time also led farmers from case study A to lose confidence in the technology. As one farmer said about body condition scoring:

> '[…] the drops were almost too big to be possible, losing a quarter of a condition score in two days. So, with that you wonder, is the system right?' (Farmer 6)

Another farmer mentioned how this loss of confidence affected uptake:

> 'I gotta be honest, the longer it's going on, the less confidence I've got in it, and the less likely I am to probably want to purchase it.' (Farmer 7)

Developers were particularly aware of the difficulties related to farmers not seeing immediate results and mentioned facing a 'big hill to climb' (Developer 2) to gain their trust back. One of them said:

> 'Farmers that have been on this trial will be the most difficult to make happy (…) Those guys saw things not working, things breaking, people up ladders, or incorrect decisions because we didn't know what was right and what was wrong.' (Developer 1)

Despite positive views held about the participation process in case study B, some participants also came across technical challenges, including lack of phone compatibility or technical glitches (e.g., the application freezing or dropping out during its use). They also expressed concerns about the application being publicised when technical issues still needed to be resolved, and about the uncertainty around the outcomes of the project, such as how the data would be used. As a participant mentioned:

> 'I think it came out too quickly on (the media) (…) we hadn't actually collected much data by that point, and it was marketed, and we were like, right, we still don't have a platform for everything to go on (…)' (Participant 10)

Another said:

> 'I think everyone's frustrated that there's a big push on that and it doesn't properly work.' (Participant 4)

5.6. Discussion

End-user participation is widely promoted to increase the adoption of innovation (Reed, 2008; Jakku and Thorburn, 2010; Eastwood, Turner and Romera, 2022). Lessons from the case studies highlight how participation can improve trust, technology design, motivation, and foster learning. Similar observations have been made in previous literature. Involvement was shown to promote enthusiasm in a system, as well as trust and a better understanding of its purpose (Oliver *et al.*, 2017). In a study by Jakku and Thorburn (2010), a participatory approach allowed farmers to gain trust and confidence in the scientists involved in the project, even though they had initial reservations. Similarly, Oliver *et al.* (2012) suggest that a benefit of co-constructing decision support tools is the ability to establish trusting relationships with the farming community and improved technology performance.

Aligning with users' needs and expectations is another recognised benefit of participation (Carberry *et al.*, 2002), and considering users' expertise (e.g., integrating local and tacit knowledge) is crucial for the development of agricultural innovations. By involving users with different perspectives and skills, participation can lead to more socially robust end results and improved technologies (Jakku and Thorburn, 2010; Lindblom *et al.*, 2017). Srinivasan et al. (2022)

reported that including different user perspectives allowed the enhancement of the relevance and legitimacy of an irrigation scheduling tool for New Zealand pastoral farms. Similarly, co-designing a smartphone application allowed the identification of users' needs and technical solutions that helped develop desirable features and functionalities (Kenny et al., 2021).

Enhanced learning outcomes are also a commonly mentioned benefit of participation processes. Jakku and Thorburn (2010) developed a framework which highlights the potential for decision support tools to act as boundary objects by facilitating communication and fostering co-learning among stakeholders involved in their development. Learning is an integral part of the participatory processes both for researchers and end-users, as they can share their thoughts and get a better insight into the decision problem being discussed (Kerselaers et al., 2015; Bruges and Smith, 2007; Rossi et al., 2014). Our study illustrates, however, that participation between developers and users can be a double-edged sword. This is sometimes acknowledged in existing literature, although often relegated in favour of an emphasis on constructing participatory frameworks. In the following sub-sections, we explore these pitfalls further and discuss how participation in technology development can be managed to overcome them. We acknowledge that participation can play a key role in adoption, but four areas of consideration are required in planning approaches (see Figure 5.1): (1) Level of stakeholder involvement, (2) Managing expectations, (3) Managing relationships, and (4) Support for learning.

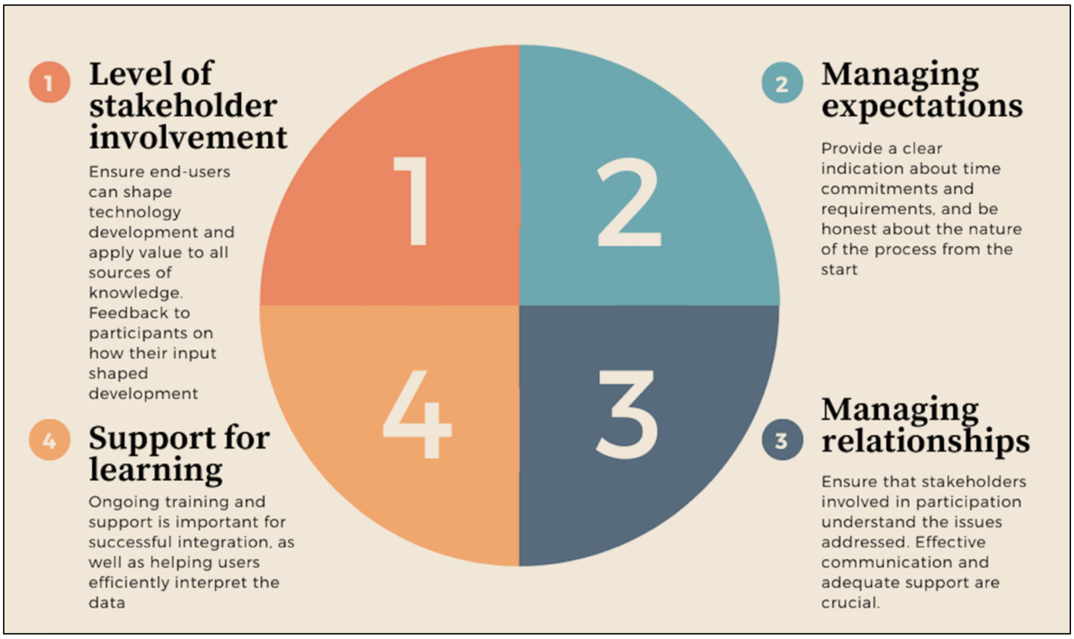

Figure 5.1: The identified key considerations for participation in technology development arising from the results

5.6.1. Level of involvement

The extent to which end-users are involved in participation is an important factor to consider. In case study A, the extent to which participants were involved was limited and progress was not necessarily shared with farmers, who mostly interacted with technicians. Being mostly exposed to the issues and not being able to witness progress could explain a loss of engagement. In case study B, there was a separation between the application developers and users. Reflecting on the literature, higher involvement is generally associated with better outcomes (Valls-Donderis *et al.*, 2014); therefore, developers should be mindful of this when planning participation. However, a balance must be found in terms of when and how to involve the right stakeholders (end-users and e.g., developers, retailers, etc.), as well as how much information is shared with them. 'More participation', such as allowing users to be in direct contact with technology developers or involving farmers in discussions about their needs when developers are unsure about being able to respond to their expectations, would likely be counter-productive. To maintain enthusiastic participation, it has been suggested to ensure that end-users can control or shape the research agenda, which would give them confidence that the project is aiming at reaching their goals (Bruges and Smith, 2007). Fostering a good level of participation also requires applying equal consideration to all sources of knowledge, taking the time to understand user perspectives (Srinivasan *et al.*, 2022), and feeding back to participants on how their input has shaped technology development.

5.6.2. Managing expectations

Though it is often assumed that early involvement of users is preferable, releasing a flawed technology into a use environment brought problems. In this study, technology failures had a negative impact on users' motivation to use technologies and on the confidence they had in them. In case study A, failures and the time taken to sort them resulted in some farmers not trusting the data, and hence not making use of it. Similarly, technical issues affected some of case study B participants' willingness to use the technology, despite a positive perception of the participation process and trust in its scientific credibility. Whilst some participants were expecting issues to occur, technology performance had a significant impact on their intention to use the technologies. This has been found elsewhere, albeit at a slightly later stage in which farmers had already bought the technology. Immature technologies impacted farmers' confidence in Automatic Milking Systems (AMS) and led to them decommissioning or reverting to conventional milking (Eastwood and Renwick, 2020). In a study by Cerf et al. (2012), farmers lacked confidence in the results of a decision support tool for crop disease control, which resulted in them not being willing to change their farming practices.

Reflecting on their experiences, technology developers from case study A thus emphasised the importance of managing users' expectations and relationships. They suggested that the optimism shown at the start of the project should be balanced to avoid users feeling disenfranchised and becoming untrusting of the data if such excitement does not transpire. Managing end-user expectations is indeed an important factor to avoid frustration, which can be particularly challenging as these vary among stakeholders (Oliver *et al.*, 2017; Steinke *et al.*, 2022). Steinke et al. (2022) note that the degree of commitment, perceptions of the prototype and the time taken to see results are all aspects that can lead to such frustration. To overcome this issue, they suggest that developers must be honest about the nature of the process from the beginning and provide regular updates about development. Clarity of expectations is also important, such as giving clear indications about time commitments (Oliver et al., 2017).

5.6.3. Managing relationships

Building trust, honesty, and managing relationships is important when using a participatory approach (Bruges and Smith, 2007), as is managing potential conflicts and flashpoints (Reed, 2008). In case study A, while developers respected farmers' workflows, they also believed the tool was further down the line than it was. In addition to the lack of stakeholder meetings, this created frustration. Some farmers also noted a lack of communication, and the decisions taken by developers affected farmers' perception of developers' understanding of farming (e.g., by giving them short notice to organise meetings). Similarly, decisions to publicly promote the application in case study B led to frustration in some users, since they were still encountering technical issues and had doubts regarding the outcomes of the project. Ensuring that the stakeholders involved in participation processes understand farming and the issues that farmers need to address is therefore key to building relationships, and so is the availability of developers in terms of providing support and effective communication.

5.6.4. Support for learning

While in case study A, developers appeared to have benefited more than participants in terms of learning outcomes, most stakeholders from case study B mentioned having learnt from the process. This was likely linked to the extent to which participants were involved, with case study

B participants having more occasions to share their thoughts with others, in contrast with case study A where opportunities for co-learning were limited.

Findings indicate the importance of having adequate support and training during prototype testing of technologies. Case study B participants were generally satisfied with the training and support provided, which helped them get a better understanding of the application. However, some also reported frustration as communication with application developers other than the lead researcher was limited. Training opportunities were less well received by some farmers in case study A. This had an impact on their perception of the participation process and the developers, particularly those with limited IT skills.

Ongoing training and support during on-farm testing is thus particularly important for successful integration into daily routines, helping users efficiently interpret the data (Busse et al., 2015). This was emphasised by Kenny and Regan (2021), who highlighted farmers' support on using the technology as important to not frustrate participants, especially those with poorer IT skills.

5.7. Limitations

Whilst both case studies gave interesting insights into the experiences of stakeholders involved in the testing of prototypes, participants' input in the overall design of the methods and technologies remained limited. In addition, the interviews were conducted at early stages of technology use, and the qualitative nature of the study means that the sample used does not allow to make generalisations. Thus, it would be interesting to study these impacts in case studies that have used other approaches to participation (e.g., user-centred design), conduct interviews at later stages to get a better insight into users' experiences, and with larger samples (and/or make use of quantitative research methods). Finally, contact details for potential participants for case study B were provided by the lead researcher, introducing a possible bias regarding the attitudes of participants towards the technology. However, those participants also reported issues with and concerns about the development process, suggesting that this bias was minimal.

5.8. Conclusion

A variety of factors influence the adoption of DLTs. However, implementing technologies does not necessarily lead to long-term use. Often, adaptation to technologies and suiting users' needs and workflows is a challenge. To address this issue, participation in technology development is often promoted. However, the level of end-user involvement, how relationships and expectations are managed, the performance of technologies and the quality of the support and training provided can have an influence on users' attitudes and engagement in participatory processes. When these aspects fail, this can impact participants' engagement, create frustration, and impact confidence and motivation to use technology, as well as trust in technology developers. In contrast, well-managed participation processes have many benefits, as they allow tools to be better aligned with users, promote learning, and facilitate adaptation. Finding the right strategies is therefore important to promote technology acceptance and uptake. Future studies could make use of larger samples or mixed methods approaches to better understand the pitfalls of participation and refine those strategies further, including in the wider digital agricultural technologies sector.

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CHAPTER 6. General Discussion

6.1. Overview

This thesis started with a question centred on how the use of Digital Livestock Technologies, or DLTs, can contribute to the enhancement of farm animal welfare. Focusing on two case studies during which end-users (farmers and farm animal welfare assessors) were involved in trialling DLTs (one for a farm assurance scheme and the other for a UK retailer), the study reveals the complexity of this central question. Determining how DLTs can help enhance animal welfare is challenging, as a variety of factors come into play. Besides the wide range of DLTs that can be found and stakeholders' varying perceptions of what is important for animal welfare and resulting management decisions; implementing DLTs in practice is far from straightforward. This means that there are many ways in which animal welfare can be impacted by DLTs. Listing promising DLT developments is not sufficient in discussing these potential impacts: the focus should also be on how these technologies will influence management practices, the possible negative consequences their implementation could have, and how end-users' concerns and expectations can be addressed to promote the uptake of DLTs. Thus, this thesis had two separate but related aims: exploring the extent to which DLTs can help address animal welfare and investigating how the uptake of DLTs can be promoted whilst minimising negative consequences. The major contribution of this thesis is that it uncovers different factors that influence the extent to which DLTs may impact animal welfare. In particular, it highlights the importance of learning and building trust among end-users of DLTs, which stakeholder collaboration can help facilitate. The findings of this thesis led to the development of practical recommendations to promote the use of DLTs in a way that considers the important dimensions of animal welfare, whilst considering the possible challenges met by end-users and other stakeholders in the process of DLT implementation on farms. A synthesis of these recommendations is presented in section 6.7.

Each chapter that constitutes this thesis brought its own, specific contributions (figure 6.1). In this chapter, I first introduce the work of this thesis by positioning it in the specific research domain of digital livestock technologies and their role in enhancing animal welfare. Then, I base my reflection on the three factors identified by Dawkins (2021) as determinants in understanding how DLTs can impact animal welfare. I start by discussing what the findings of this thesis told us about the potential of DLTs to address different dimensions of animal welfare. Then, I discuss how DLTs can influence users' perceptions of animal welfare and lead to practical improvements, and the role of learning and building trusting relationships in promoting change. Finally, I examine the relevance of using collaborative approaches to the development of DLTs along with their challenges, before presenting the limitations of this thesis and research perspectives.

My work offers an overview of what can promote or hinder animal welfare enhancements when using DLTs. By bringing together these elements, I highlight the complex nature of the journey of DLT implementation and use faced by end-users and other stakeholders. All these elements are presented successively to meet the aims of this thesis and to suggest practical recommendations and strategies to promote animal welfare enhancements with DLTs.

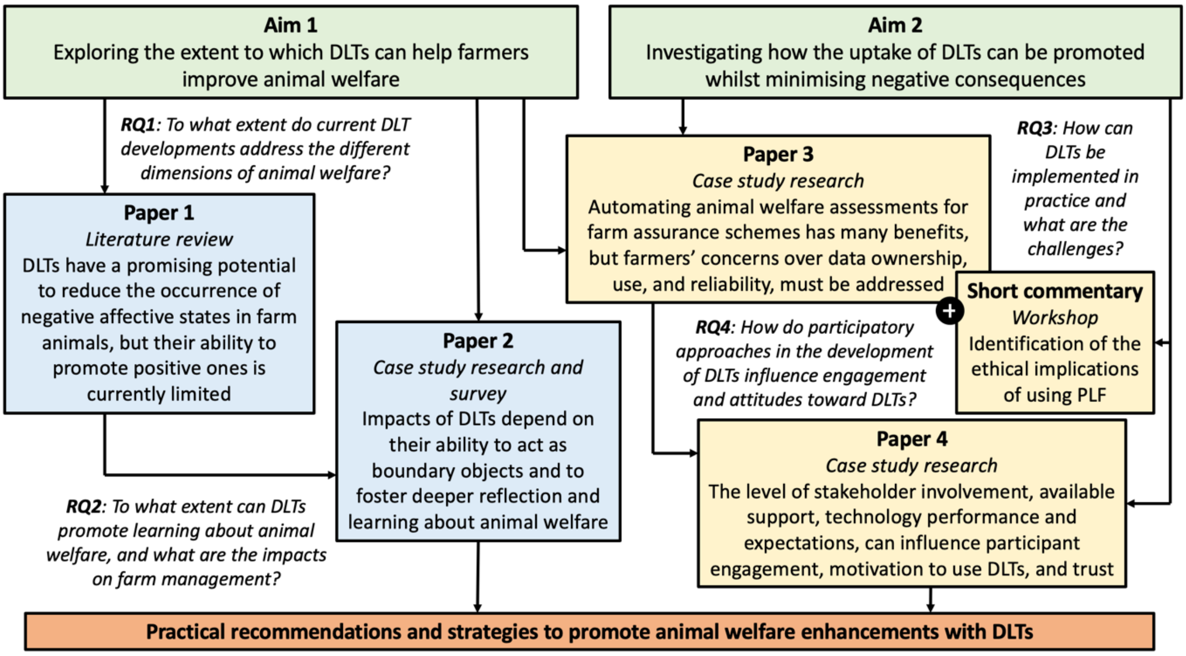

Figure 6.1: Synthesis of the research papers of this thesis

6.2. Enhancing animal welfare with Digital Livestock Technologies: a conundrum

The important role that DLTs can play in enhancing farm animal welfare is increasingly being promoted. As I have highlighted in chapter 2, many solutions are being developed for this specific aim, with the hope that their use will help address concerns around farm animal health and welfare as a result of more efficient assessment and management (Berckmans, 2014; Buller *et al.*, 2020; van Erp-van der Kooij and Rutter, 2020; Ingenbleek and Krampe, 2022). Despite the potential benefits of these emerging technologies, a growing amount of critical literature interrogates the promises of what some call a 'fourth agricultural revolution'; countering claims that agricultural technologies, such as DLTs, will necessarily 'change production systems beyond recognition leading to increased productivity, reduced environmental damage, and socio-economic benefits' (Rose et al., 2022, p.1-2). General uncertainties over data ownership and control, power imbalances, impacts on farmers' identities and the way they work, and a lack of attention to farmers' needs resulting in some failing to adapt and learn how to use digital agriculture technologies, have all raised questions about their role and their social and ethical implications (Eastwood and Renwick, 2020; van der Burg, Bogaardt and Wolfert, 2022). In livestock farming more specifically, this also includes concerns over farmers' relationship with their animals, the risks of facilitating the management of intensive livestock systems with little opportunities for good animal welfare, or risks of impacting traditional husbandry skills (Cornou, 2009; Butler, Holloway and Bear, 2012; Werkheiser, 2018; Kling-Eveillard *et al.*, 2020; van der Burg, Bogaardt and Wolfert, 2022).

These implications have led to reflections about whether DLTs are 'an animal's friend or foe, and a farmers' panacea or pitfall?' (Wathes *et al.*, 2008), whether they prioritise farm production efficiency over animal welfare (Rowe, Dawkins and Gebhardt-Henrich, 2019) or whether their use improves or damages animal welfare (Dawkins, 2021). Anticipating negative consequences is crucial, but fewer studies have involved end-users (e.g., farmers) and other relevant stakeholders (including the animals themselves) in exploring the impacts of DLTs on animal welfare. Some studies have done so to explore, for example, impacts on the human-animal relationship (Kling-Eveillard *et al.*, 2020), the coping capacity of dairy cows when changing from conventional to automatic milking (Weiss *et al.*, 2004), or the re-capturing of bovine life with Automated Milking Systems (AMS) (Holloway, Bear and Wilkinson, 2014). However, the complexity of animal welfare coupled with that of implementing DLTs on farms means that more studies are needed to increase our understanding of these impacts. My thesis thus participates in these discussions by exploring the drivers and barriers of enhanced farm animal welfare with DLTs, based on empirical research.

6.3. The importance of positive animal welfare

Before delving into the case studies, I started by exploring the ability of DLTs to address the different and complex dimensions of animal welfare through a review (chapter 2), supported by a workshop I have organised (appendix 1). I first identified a wide range of PLF technologies and their development stages to distinguish better between technologies that were commercially available and those that were at earlier stages of development. I discussed their potential animal welfare benefits and risks, including the potential to detect health and welfare compromises at early stages, the monitoring of livestock at both individual and group-level, or the possible negative impacts on the human-animal relationship. The findings of this thesis add to the existing literature on the potential impacts of DLTs on animal welfare (Berckmans, 2014; Rowe, Dawkins and Gebhardt-Henrich, 2019; van Erp-van der Kooij and Rutter, 2020) by exploring the ability of DLTs to influence animals' affective states based on the Five Domains Model (Mellor *et al.*, 2020). Affective states, influenced by the range of negative and positive experiences that animals live, provide useful indications of animals' overall welfare states. This makes the FDM a relevant framework to explore the extent to which DLTs can impact animal welfare, and thus address the first research question of this thesis (RQ1). Whilst I highlighted the important potential of existing DLTs to address the different dimensions of animal welfare, I also found that commercially available DLTs generally emphasised reducing the occurrence of negative affective states instead of promoting positive ones. These findings coincide with other studies that have emerged since. Stygar et al. (2021), for example, found that PLF developments for dairy cattle had a low potential to address the 'appropriate behaviour' principle of the WQ® protocol, which captures a good-human-animal relationship, animals' expressions of behaviours (e.g., social behaviours) and positive emotional states. Similarly, Gómez et al. (2021) and Larsen, Wang and Norton (2021) identified a lack of DLTs that can be used to assess animals' affective states (both positive and negative) in the pig sector. The findings also concurred with previous findings from Fogarty et al. (2019) in sheep farming, who highlighted a lack of sensors that applied to the 'mental state' domain of the FDM.

These findings do not imply that animal welfare cannot be enhanced with DLTs, as my research clearly demonstrated their potential to help farmers make management decisions that can reduce the intensities of negative affective states such as environmental discomfort, stress, or pain (chapters 2 and 3). However, I emphasised that negative affective states can at best be neutralised: they do not necessarily lead to anything more than positive welfare states that are short-lived (Mellor and Beausoleil, 2015). Promoting positive animal welfare states, which is integral for good animal welfare, requires animals' ability to live positive experiences, such as play or adequate social interactions (Boissy *et al.*, 2007). Thus, to meaningfully impact animal welfare, I argued that a greater emphasis should be placed on DLTs that not only allow minimising negative affective states but can also promote positive ones. To encourage the development and adoption potential of such DLTs, I emphasised the need to highlight the benefits of promoting positive welfare, such as the effect on productivity and on farmers' own welfare (Vigors and Lawrence, 2019).

By exploring the potential of DLTs to address the different dimensions of animal welfare, my results triggered reflections on how this potential could be translated into practice and on the need to identify the impacts of DLT implementation on management practices. I make the point that exploring the potential of DLTs to help enhance animal welfare requires investigating what farmers learn from the data and whether farm management decisions are adapted in a way that considers the promotion of positive animal welfare states (chapters 2 and 3).

6.4. The role of learning in promoting changed management

In a study on the ethics of using Automated Milking Systems (AMS), Driessen and Heutinck (2015, p.10) state that 'a normative evaluation of something like the AMS can only be understood as part of a wider shift in practices and in terms of an intricate co-evolution process between partly material changes in technological systems and behavioural practices of both farmers and cows.' They argue that with new technologies, new roles are configured, experiences are generated, and the nature of humans, animals, and their relationships, is also subject to change. The findings of this thesis further suggest that introducing new technologies, through processes of learning, can also create a shift in end-users' perceptions and approaches to animal welfare and its management on farms (chapter 3). Learning indeed underpins changes in attitudes and behaviour towards improved farm animal practices and can help shape social norms within the farming community (Balzani and Hanlon, 2020). Thorburn et al. (2011) even argue that focusing more on learning experiences than on the use of DLTs may make a more meaningful contribution to sustainable farming practices.

According to Lundström and Lindblom (2021), learning is required to successfully implement technologies on farms and to manage and provide good care in socio-technical systems. The findings of this thesis align with this statement and further highlight that the type of learning is an important element to consider in understanding the extent of these changes. Indeed, implementing DLTs on farms does not necessarily mean that these will be used in an optimal way in relation to animal welfare. As I argued in chapter 2, impacts may vary depending on whether DLTs will strictly be used to cure symptoms once they appear, as opposed to preventing issues arising in the first place. Drawing on the work of Star and Griesemer (1989), I argue in chapter 3 that impacts on farm management practices and their significance to the enhancement of farm animal welfare is likely to depend on DLTs' ability to act as boundary objects; facilitating stakeholder communication around animal welfare and allowing stakeholders to collaborate and co-learn. I found that whilst both DLTs fostered learning that could help farmers improve their welfare management strategies such as by becoming more proactive and efficient in dairy cow lameness management (chapters 3 and 4), which is a process characteristic of single-loop learning, the smartphone application used in case study B also fostered a re-framing of values and beliefs (double-loop learning) in relation to the importance of animals' emotional wellbeing and that of providing opportunities for positive animal welfare (chapter 3).

I argued that the greater interpretive flexibility of the smartphone application and the participatory approach taken to its development generated learning and greater awareness of *how* and *why* animals behave in different ways, as stakeholders were able to share their views and discuss their understanding of animals' behavioural and emotional expressions. By acting as boundary objects, DLTs can encourage communication and bridge gaps between different stakeholders such as farmers, assessors, technology developers, researchers, or industry workers (chapters 3 and 5). This can help stakeholders get a better understanding of the purpose of using DLTs and their roles in improving farm animal welfare. Social learning between stakeholders is often considered a positive outcome of participatory approaches, as it allows participants to turn differing perspectives and knowledge into concrete actions (Jakku and Thorburn, 2010; van Paassen, de Ridder and Stroosnijder, 2011; Reed *et al.*, 2016; Colnago, Rossing and Dogliotti, 2021; Ryschawy *et al.*, 2022). Participatory approaches to training, for example, encourage learning about data and building capability to effectively use DLTs (Eastwood *et al.*, 2019)

In a study on AMS, Lundström and Lindblom (2021) suggested that implementing technologies results in end-users entering a continuous learning process, learning how to interpret and apply data in practice to manage cows at both individual and group levels. They argued that for farmers to be successful in dairy production, farmers need to adapt their practice and technology to their situation and improve practices 'that make technology and knowledge work' (p.400), which may depend on how farmers interpret cow behaviour and requires attentiveness and knowledge of cows. In light of this statement and the findings of this thesis, I suggest that the extent to which animal welfare can be enhanced with DLTs is thus likely to depend on what end-users learn when interacting with these systems, and how this informs welfare management practices. Addressing the second research question of this thesis (RQ2), I argue that DLTs that generate a greater understanding and reflection on the different dimensions of animal welfare may lead to more positive changes in management practices and animal welfare than if learning was restricted to improving existing strategies.

Evaluating the impacts of DLTs on animal welfare should thus not only be based on whether specific technologies have been implemented on farms, or on how 'technologically advanced' these are: it should also focus on how farmers interact with these technologies, what they learn from using them, and how this influences management practices. Learning, however, varies significantly depending on individuals, farming systems, technologies, and the institutional environment (Nettle *et al.*, 2022), and farmers' willingness to learn will directly influence how technologies integrate into their work practices and shape the many different paths that farmers can take (Lundström and Lindblom, 2021). DLTs are themselves heterogeneous: they follow different development trajectories, and their impacts on livestock systems will vary (Stræte *et al.*, 2022). This makes the implementation of DLTs often challenging, with difficulties in predicting potential disruptions. This can exacerbate uncertainties and thus challenges in building trust among end-users.

6.5. Building trusting relationships

Through chapters 2 and 3 of this thesis, I have shown that more significant welfare improvements may be achieved if DLTs can help promote positive affective states and foster learning among users about these important dimensions. In the 4th and 5th chapters, I was able to identify other challenges that revealed the complexity of enhancing animal welfare with DLTs and highlighted the need to take a holistic approach, including focusing on the challenges of DLT implementation and ways to mitigate them to promote trust among end-users. As Rijswijk et al. (2023, p.1) argue, digitalisation[11] involves, 'besides (in many cases radical) technological change, social, institutional and economic change and is often synonymous with disruption, meaning that the outcomes significantly affect individuals, businesses, industries or society as a whole'. They further added that because these outcomes cannot be precisely predicted, considerable uncertainty is often

[11] According to Rijswijk et al. (2023, p.1): 'Digitalisation is a challenging process that goes beyond digital technologies and their use within an organisation. It is argued that digitalisation should be understood as a socio-technical transition, whereby current technologies and related processes are replaced or supplemented by complex digital technologies such as the Internet of Things (IoT), augmented reality, Artificial Intelligence (AI), Blockchain, and Digital Twins'.

created. Due to the complex interactions between the social, the cyber and the physical (Rijswijk *et al.*, 2021), the implementation of technologies on farms is particularly challenging. There is therefore a need to go beyond technology acceptance and to understand *how* end-users use and interact with technologies, as opposed to focusing on the binary use or non-use of technologies (Lundström and Lindblom, 2021; Rose *et al.*, 2022). In this thesis, trust relationships between end-users, developers, researchers, and technology, were found to play a major role in the successful implementation of DLTs (research question 3, RQ3).

This was particularly emphasised in chapter 4, in which I investigated the potential of a machine-learning 3D camera to automate animal welfare-related data collection (i.e., Body Condition Scoring and mobility) for assurance purposes due to its potential implications for animal welfare, but also for farmers, the wider food industry, and consumers (van Erp-van der Kooij and Rutter, 2020; Ingenbleek and Krampe, 2022). I identified some of the expectations and concerns that farmers had about the use of the camera in this context. Findings indicated that farmers saw important benefits in automating aspects of animal welfare assessments with the camera, including improved health and welfare management and improved consumer trust through greater production transparency. They also mentioned the benefit of being able to increase fairness thanks to greater consistency in animal welfare data collection, as well as saving time and costs associated with manual welfare assessments. However, farmers also reported important concerns over data ownership, reliability, and use, which are concerns that are often highlighted in relation to digital technologies (Wiseman *et al.*, 2019). Some showed reluctance in sharing their data, especially where there were doubts regarding the reliability of the data and whether these data may be accessible by third parties. Some farmers also raised concerns about the possibility of making the use of the camera a future requirement and were concerned about possible negative repercussions if the data was incorrect or misused.

Issues of trust were also identified by participants from the workshop due to a lack of technology validation (appendix 2) and by participants from both case studies (chapter 5), where repeated technology failures and inadequate communication with technology developers impacted end-users' confidence in DLTs and motivation to use them. Trust is crucial for effective information exchange among value chain actors to foster cooperation and decision-making, and a lack of it can hinder the uptake and use of digital agricultural technologies (de Vries *et al.*, 2022). Similar results were found in a study on the grains industry, in which Jakku et al. (2019) found that despite the perceived benefits of smart farming such as improved efficiency and industry decision-making and traceability; there were also concerns about data accuracy and reliability, data handling and a lack of trust regarding third-party use of the data. They stated that issues of trust and transparency between farmers and agribusinesses contributed to a lack of willingness of farmers to engage with these technologies. They also highlighted concerns over data sharing, which they argued are related to the dynamics of power relations between industry stakeholders. They mentioned that current institutional arrangements for data ownership do not provide the necessary trusted environment to encourage data sharing. These concerns over a lack of effective regulatory frameworks and of clarity around data use and privacy further highlight the need to address these social and political issues to design more socially responsible digital agriculture technologies (Gardezi *et al.*, 2022).

In their study, Gardezi et al. (2022) indeed suggest that despite a generally optimistic view of the potential of digital agricultural technologies, such as achieving improved farming decisions, these can change the nature of farming, and redefine social practices and meanings in agriculture. In addition, perceived behavioural control is a highly influential factor in farmer behaviour – thus a lack of trust and agency is unlikely to lead to improved decision-making (Rose, Keating and Morris, 2018). Farmers' concerns about implementing DLTs should therefore be adequately identified and addressed if these are to be implemented and used effectively, and thus lead to meaningful outcomes in relation to farm management, animal welfare, and building consumer trust by giving them access to animal welfare information, enabling traceability and verifying adherence to animal welfare standards (chapters 3 and 4). Failing to address these concerns is likely to undermine the potential role that DLTs may play in enhancing animal welfare. As Rijswijk et al. (2021, p.86) state: 'past experiences of agricultural and rural modernisation have demonstrated that *technology push* without addressing the underlying socio-economic and ecological dimensions risk to generate unpleasant or unwanted outcomes'.

Digitalisation also has the potential to disrupt advisory services, requiring advisors to reassess their skills, practices, and services to adapt to these new ways of working and demands to facilitate learning (Eastwood et al 2019; Ingram and Maye, 2020). Addressing these issues implies opening dialogues between technology developers, policymakers, researchers, advisors, and farmers, to foster mutual trust through increased transparency (Busse *et al.*, 2015; Brier *et al.*, 2020). Through participatory and co-development approaches, stakeholders can discuss 'how, when, and what a technological innovation could be, and what it should be, to stabilise' (Stræte et al., 2022, p.9), and build capability to use DLTs effectively (Ingram and Maye, 2020). The relevance of using participatory approaches in the development of DLTs was highlighted throughout this thesis and is discussed in the following section (6.6).

6.6. Collaborating to generate effective solutions to animal welfare issues

In light of these findings and the complex processes of DLT implementation, the outcomes of this thesis clearly demonstrated the need for trans-disciplinary effort and a systems perspective, involving end-users (e.g., farmers), advisors, researchers, developers, and other relevant stakeholders in co-creation, rather than relying on 'technology push'. This can be facilitated during the participatory development of DLTs which, by acting as boundary objects, can help bridge gaps between different stakeholders even when they share different perspectives, and promote a shared understanding of the purposes of DLTs and their implications for animal welfare, as I have highlighted in chapters 3 and 5. Through these approaches, developers and researchers can get a better understanding of end-users' needs and concerns, as well as be able to use different stakeholders' expertise to optimise the design of DLTs whilst giving participants feelings of ownership (chapters 4 and 5). Adopting a user-centred approach is often promoted to help identify and address end-users' concerns and promote the development of technologies that are better suited to their needs (Jakku and Thorburn, 2010; Klerkx and Nettle, 2013; Eastwood *et al.*, 2016; Eastwood, Turner and Romera, 2022). Similar benefits were identified in other contexts, such as that of climate-change adaptation, where participatory approaches were found to promote enhanced agricultural adaptation to climate change and to encourage the adoption of climate-change mitigation practices (Nettle *et al.*, 2022). In a case study on the use of white grain sorghum for silage on dairy farms, Nettle et al. (2022) found that using a multi-actor approach 'enabled relationships to be built so that sharing, trialling, and implementation of the alternative feed source was understood and adopted by many farms' (p.15). Thus, carefully managed participatory approaches have an important potential in promoting the adoption and successful implementation of DLTs. Through processes of articulating ideas and sharing of knowledge and risks, principles of co-innovation can also encourage the building of social relationships (Paschen *et al.*, 2021).

There are, however, challenges in managing participatory approaches to the design of digital innovations, such as time constraints, difficulties in maintaining participant engagement, or difficulties in aligning diverging interests (Klerkx and Nettle, 2013; Kerselaers *et al.*, 2015; Steinke *et al.*, 2022). In the fifth chapter, I found that participation can also be a double-edged sword. The different approaches that researchers and technology developers from the case studies took in the processes of participation influenced end-users' engagement and attitudes towards the processes. I found that when these aspects fail, this can create frustration, and impact end-users' confidence and motivation to use technology, as well as their trust in the technologies and their developers. In answer to the fourth and last research question (RQ4), I highlighted the importance of finding the right balance in terms of the extent of stakeholders' involvement, as well as that of clarifying and managing end-users' expectations, to avoid them being disenfranchised if the optimism shown at the start of a project doesn't transpire in its outcomes. I also emphasised the importance of effective communication and of having an adequate understanding of participants' motivations, as well as providing them with appropriate support and training. This concurs with findings from Steinke et al. (2022), who emphasised the importance of managing stakeholders' expectations. Similarly, Lundstrom et al. (2015) also identified a lack of transparency and effective communication as pitfalls in participatory approaches and emphasised the need to strategically manage these processes and find the right stakeholders to involve. They suggested, for example, appointing a user advocate to mediate between end-users and technology developers.

Despite the many benefits of participation, it would therefore be wrong to assume that these processes will straightforwardly encourage the uptake of DLTs. This is not always acknowledged in the literature, which often promotes participatory approaches as a panacea to the creation of relevant, usable decision-support tools for achieving social sustainability in agriculture (Gardezi *et al.*, 2022). The findings from my thesis thus contribute to the existing literature by highlighting that this is an aspect that needs to receive more attention. As stated by Duru (2013, p.86): 'despite their strengths, participatory methods do not always lead to relevant change'. Gardezi *et al*. (2022) indeed warned about the challenges of participatory approaches using the example of living labs which, whilst having the ability to enhance users' trust and encourage co-creation through 'real-life' testing of a product or service, often focus on instrumental business value as opposed to achieving broader societal goals such as addressing ethical concerns. They advised broadening participation and focusing on aspects beyond economic profitability, such as the ethical and normative principles of sustainability (e.g., work safety, soil health and rural quality of life).

Ineffective collaboration could undermine the potential benefits and opportunities of co-innovation, indicating the importance of carefully designing participatory approaches (Paschen *et al.*, 2021). The dynamic nature of innovation means that there is no 'true' approach or a uniform model for implementation (Ingram *et al.*, 2020). Thus, in participatory approaches, it is often required to 'negotiate different institutional, social, and cultural contexts', and to involve facilitators to successfully maintain stakeholder engagement whilst managing inherent unpredictability (Ingram *et al.*, 2020, p.67). Paschen *et al*. (2021) argue that co-innovation processes require continuity of personnel and institutional support for their successful functioning and institutionalisation, as well as the commitment of all stakeholders to build and maintain trust and social capital between stakeholder groups. They suggest that implementing and sustaining practices of inclusivity require careful design and facilitation, with a key element of co-innovation being the involvement of 'innovation brokers' to co-facilitate these processes and to connect different stakeholders across agricultural industry sectors. Stræte et al. (2022) further suggest that for technologies to make significant, positive social impacts, it is crucial to identify technologic-specific supporting functions that will help stimulate transitions to 'smart farming'. Such support must be targeted to the different stages of technological innovation readiness, including those identified in the Balanced Readiness Level assessment (BRLa) which are: technological, market, regulatory, social acceptance, and organisational. Whilst investigating the role of advisors was outside the scope of this thesis, the findings further highlighted the importance of providing adequate support in promoting the adoption and effective use of DLTs.

The participatory development of DLTs for more inclusive processes and responsible innovation is therefore important to mitigate the challenges imposed by socio-technical systems, and adequate support is required to achieve this. Whilst the findings of this thesis have highlighted the importance of carefully designed participatory processes to help anticipate diverse transition pathways, more research is needed on the possible benefits and pitfalls of such approaches, as well as on the need to involve facilitators to ensure that the important potential of these approaches in encouraging the uptake of DLTs and embedding best practices to enhance animal welfare is maximised, whilst being able to mitigate the risks of impacting end-users' engagement and the adoption potential of DLTs.

6.7. Recommendations

Based on the findings of this thesis, I suggest seven recommendations for the enhancement of animal welfare using DLTs. Most of these recommendations concur with the current literature e.g., the importance of focusing on learning and how farmers make use of technologies (Lundström and Lindblom, 2018, 2021; Rose *et al.*, 2022), the importance of providing clarity on data ownership, reliability and use (Wiseman *et al.*, 2019) and that of involving end-users in the participatory development of smart technologies (Jakku and Thorburn, 2010; Thorburn *et al.*, 2011; Eastwood, Edwards and Turner, 2021). More specifically, the present recommendations highlight the need to take a holistic approach when aiming to achieve animal welfare enhancements with DLTs, including the need to focus on aspects of positive animal welfare and on the possible negative consequences, both for farmers and their livestock, which have often received less attention. These recommendations are addressed to a range of stakeholders involved in the development of DLTs and regulators, including technology developers (e.g., engineers), scientists (both in computer and animal science but also social sciences), retailers, and policy-makers. Whilst some of these recommendations could be envisaged in the short-term (recommendations 4, 5, 6, and 7), others may require a longer time frame for their implementation due to the need for further research and long-term studies (e.g., recommendations 1, 2 and 3). The successful implementation of these recommendations will, however, depend on stakeholders' willingness to address important and complex questions such as data management and ownership, and whether the importance of involving end-users in co-design will be further recognised.

- **Recommendation 1**: greater emphasis should be placed on developing DLTs that can promote positive affective states in addition to reducing negative ones.

- **Recommendation 2**: increase the acceptability and adoption potential of technologies aimed at encouraging positive animal welfare by highlighting, for example, its benefits on farm productivity.

- **Recommendation 3**: greater attention should be paid to the ways end-users interact with DLTs. For example, by focusing on whether they can foster learning and a re-framing of values and beliefs in relation to animal welfare, and whether they encourage changed management practices.

- **Recommendation 4**: provide better clarity to end-users on data ownership and how the data is going to be used, and who will be able to access it

- **Recommendation 5**: build end-user trust by providing evidence of technical performance and data accuracy and reliability, and technology validation.

- **Recommendation 6**: consult with end-users and other relevant stakeholders to discuss best practices on using DLTs, especially when implementing DLTs in contexts such as farm assurance schemes.

- **Recommendation 7**: encourage carefully planned end-user participation in the development of DLTs to better identify and address their needs and concerns. Key considerations include: the level of stakeholder involvement, managing expectations and relations, and providing adequate support for learning.

6.8. Limitations and research perspectives

There were several limitations to this thesis work, which I highlight in this section alongside suggestions for further research.

The first concerns the methods used, which are closely linked with the challenges encountered during the thesis (see section 1.6.2). Most notably, the COVID-19 pandemic had an important impact on the methods I was able to use, which resulted in changes to my initial research plans. Whilst the use of qualitative research methods such as in-depth interviews conducted with the different participants involved in the case studies allowed me to obtain a rich and detailed account of their experiences with DLTs and to better understand the opportunities and challenges of DLTs to enhance animal welfare, my aspiration at the start of the project was to take a mixed-method approach to obtain a more complete picture. More specifically, conducting farm animal welfare assessments before and after the use of the camera system in case study A would have allowed me to explore potential links between changes in animal welfare levels and changes in management practices following the use of the system. However, travel restrictions imposed by the COVID-19 pandemic meant that undertaking this research was not possible. These restrictions also impacted case study A developers' ability to travel to farms to fix the technical issues they encountered, which meant that most farmers were not able to make use of the technology by the time of the second round of interviews. To date, studies that aimed to explore the potential impacts of DLTs on animal welfare have done so through reviews of DLTs and their ability to address different dimensions of welfare, or by conducting interviews with farmers about their experiences, as I have done during my project. However, to my knowledge, no studies have assessed the impacts of using DLTs on animal welfare using a before and after implementation approach, thus this constitutes an interesting approach for future studies. Indisputably, there are challenges to this approach, since there are many variables that can affect animal welfare levels over time. Combining these assessments with in-depth interviews with farmers can help mitigate this issue, such as by identifying any on-farm events that would have affected the results. There are also important time constraints to this approach since sufficient time should be allowed between the 'before' and 'after' implementation steps for meaningful differences to be observed in terms of farm management and animal welfare impacts.

Further studies would also benefit from diversifying methodological tools and involving more extensive ethnographic studies, including, for example, on-farm observations to gain further insight into these impacts and more in-depth data. Whilst this would not have been possible in the context of my study due to financial and time constraints, adding on-farm observations to the welfare assessments and in-depth interviews to investigate farmers' interactions with the technologies and how farmers make decisions based on these technologies can also be an interesting approach to get a more complete picture of the impacts of DLTs on farm management and animal welfare.

Another limitation imposed by the COVID-19 pandemic was the timing of the interviews conducted with end-users from case study A. Indeed, only two out of 11 farmers were making use of the camera system, which means that the results I obtained mostly related to farmers' perceptions of the issues explored, as opposed to being based on their actual experiences of using the camera. Similarly, the timeline of this thesis means that interviews with stakeholders in case study B were conducted at a time when only farm assessors were making use of the application. Whilst these interviews allowed me to gain highly relevant information, it would have been interesting to explore the impacts of this application at a time when assessments were also conducted by the farmers themselves.

Another limitation of this study was the possible bias introduced by the case studies. In both cases, the DLTs were implemented on farms that were either involved in farm assurance scheme programmes, or with retailers that were known to drive higher animal welfare standards and innovation. This means that there was a possible bias towards end-users already in a positive mindset regarding using new technologies and being proactive in driving animal welfare improvement. For future studies, it may thus be interesting to conduct further research involving farmers that have implemented DLTs in other contexts, as well as to explore the views of those farmers who are more reluctant to the idea of using DLTs. This would allow for a more comprehensive understanding of farmers' expectations and concerns about the use of DLTs.

Despite the limitations of this thesis work, and the possible lack of depth of some aspects of the study due to the constraints explained above, important knowledge was generated, in line with earlier discussions and presentations of findings. Indeed, whilst it is not possible to generalise, the descriptive approach and resulting findings of this study provided relevant and deep insight into the benefits and challenges of implementing DLTs to improve farm animal welfare. These insights were shared during international conferences, peer-reviewed and, in part, published in scientific journals. The first paper (chapter 2) has, at the time of writing, attracted over 25,000 views from around the world.

6.9. References

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CHAPTER 7. General Conclusion

The initiative of this thesis stemmed from what can appear to be a simple question: do digital livestock technologies actually help enhance farm animal welfare? The initial objective of this thesis was to answer this question, taking both the animals' and end-users' perspectives through a combination of 'before and after' animal welfare assessments and in-depth interviews with farmers. However, my plans had to be reconsidered following a global health crisis (the COVID-19 pandemic), and challenges met during one of my case studies.

The need to adapt my work was, however, what made me realise the complexity of the question I was aiming to answer, and the many factors that needed exploring in attempting to answer this question. Whilst I could not perform the animal welfare assessments due to circumstances beyond my control, the challenges faced by farmers in the first case study and the farm assessors from the second case study during the processes of implementation were equally as important to explore, and provided a different angle to the initial research question. The opportunities and challenges of using DLTs to enhance farm animal welfare highlighted in this thesis are numerous, and the complexity of implementing DLTs in practice adds further uncertainty. Enhancing animal welfare with DLTs is indeed not straightforward, as there are several influencing factors which include the types of DLTs used and their applications (chapters 2 and 3), the ability of DLTs to promote learning and a re-framing of values and beliefs (chapter 3), whether stakeholders' expectations and concerns have been identified and addressed (chapter 4), and whether and how these stakeholders have been involved in early discussions (chapter 5). These findings have, in particular, highlighted the need to promote efficient stakeholder collaboration as a way to foster learning and to build trusting relationships to maximise the potential of DLTs in helping enhance farm animal welfare.

The first paper of this thesis was a useful starting point to reflect on other important aspects that needed exploring. Whilst I highlighted DLTs' important potential to reduce the occurrence of negative affective states and revealed the lack of focus on promoting positive ones using the Five Domains Model, I also pointed to the importance of focusing on whether management practices would be adapted to minimise negative consequences and maximise benefits to welfare. Whilst the case studies used did not allow for measuring impacts on animal welfare and management practices quantitatively, I highlighted that these impacts were likely to depend on DLT's ability to act as boundary objects, by promoting discussions between stakeholders and a re-framing of values and beliefs about animal welfare (chapter 3). I also highlighted the importance of encouraging collaboration between stakeholders (e.g., industry, researchers, end-users…), which I found particularly relevant in the context of farm assurance schemes due to the possible implications for animals, farmers, but also for the wider food industry and consumers (chapter 4). In chapter 4, I revealed some of the important perceived benefits of automating aspects of animal welfare assessments, such as improved consistency in data collection, improved animal welfare management and the ability to increase fairness in data collection processes. However, I also highlighted the importance of providing farmers with better clarity about data ownership, use, and reliability, as failing to do so could negatively impact end-users' engagement with DLTs or even result in their rejection. Lastly, I highlighted the need for increased collaboration between end-users and other stakeholders, such as through the participatory development of DLTs (chapter 5). I found that despite the many identified benefits of these processes (e.g., better aligning DLTs with users' needs, promoting learning, and encouraging feelings of ownership), participation with stakeholders also presented important challenges. When managed inadequately (e.g., in terms of how stakeholders are involved, how they are supported and how relationships and expectations are managed), participation can lead to frustration and impact end-users' engagement and attitudes towards the processes, as well as their motivation to use the technologies. This highlights the fact that, in contrast with mainstream views, participation does not necessarily linearly promote technology uptake.

This work was undertaken in line with the critical literature on agriculture digitalisation, which counters the persisting idea that technological change (and resulting improvements to animal welfare) is a quick and linear process. I consider that, despite the challenges encountered, the originality of the research comes from the use of case studies that allowed me to explore the experiences of a range of stakeholders involved in the development and trialling of DLTs that were both aimed at improving animal welfare, but that differed greatly in terms of their technical complexity and methodology, and thus in their potential to help enhance farm animal welfare. Through my findings and resulting recommendations, I hope to have contributed to the important discussions around the potential of DLTs to enhance farm animal welfare, and to have inspired future research aiming at maximising this potential, whilst minimising and addressing the possible social and ethical consequences.

Such future research may include the use of a diverse set of methodological tools to assess the impacts of the use of DLTs on animal welfare, including a combination of quantitative and qualitative methods and a greater focus on ethnographic studies (e.g., using on-farm observations to investigate farmers' interactions with DLTs and how they influence decision-making). Evaluating the impacts of the use of DLTs on animal welfare could also benefit from quantitative approaches, such as undertaking farm animal welfare assessments over the long term. Indeed, whilst I was able to explore the experiences of a variety of stakeholders, I was not able to explore that of animals, due to the constraints raised in the limitations. Future work may also include a focus on consumers' perceptions of the use of DLTs, which is often a neglected area despite consumers' crucial role in driving animal welfare enhancements.

The findings of this thesis have important practice, education, policy, and research implications, relating to animal welfare and beyond. Many of these findings can indeed apply to the wider smart agriculture sector, including the need to focus on stakeholder collaboration to promote learning and trust for the effective use of technologies towards more sustainable, welfare-friendly farming systems.

Appendix 1: Workshop outline

'***Current developments in Precision Livestock Farming (PLF) technologies: What can we measure and what are the welfare benefits and challenges?***'

The workshop was conducted online (Zoom) on Friday 20th November 2020

10.00	**Introduction**
10.15	**Presentation 1 by Prof. Mark Rutter** (Harper Adams University)
	Introduction to PLF - use of technology in welfare monitoring
	Questions
10.50	**Presentation 2 by Dr Isabelle Veissier** (INRAE)
	Potential benefits and risks of using Precision Livestock Farming technologies to manage animal welfare – Recent developments at INRAE
	Questions
11.20	Break
	Networking
11.50	**Activity 1**
	Developments in PLF technologies and benefits to welfare
12.25	**Activity 1 - discussion**
1.00	Lunch break
2.05	**Presentation 3 by Dr Emma Baxter** (SRUC)
	Positive animal welfare and PLF
	Questions
2.35	**Activity 2**
	PLF risks and challenges to welfare
3.10	Break
3.25	**Activity 2 - discussion**
4	**Presentation 4 by Dr Ian Werkheiser** (University of Texas Rio Grande Valley)
	Underexamined Ethical Perspectives on PLF
	Questions
4.45	**End of workshop**

Appendix 2: Short commentary

Animal welfare and other ethical implications of precision livestock technology

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Authors' contributions: Juliette Schillings (estimated percentage contribution: 60%): Conceptualisation, methodology, investigation, data curation, writing, original draft preparation, editing. Richard Bennett: Supervision, reviewing, and editing. David Rose: Supervision, writing, reviewing, and editing.

Abstract

In this commentary, we explore the risks and challenges associated with Precision Livestock Farming based on an online workshop with over 70 international animal welfare experts, policy-makers, NGO, students, farmers and industry staff.

Keywords: Animal health; animal welfare; ethics; precision livestock farming; technology

The term Precision Livestock Farming (PLF) is generally associated with technologies that allow the real-time, automated and continuous monitoring of farmed animals (Berckmans, 2017), such as cameras, sensors, and sound devices, which are increasingly powered by artificial intelligence and allow the collection and interpretation of data. They are seen as one of the promising solutions to sustainable livestock farming, helping farmers to improve productivity, whilst limiting environmental degradation, sustaining livelihoods and improving animal health and welfare. Whilst there has been considerable attention placed on the opportunities offered by PLF technologies, relatively less scholarly interest has been afforded to its risks (Werkheiser, 2020).

Our efforts described below were inspired by a small number of research papers exploring the ethical implications of PLF (e.g. Bos *et al*., 2018; Werkheiser, 2018, 2020), as well as research into the social and more-than-human consequences of robotic milking technologies (Bear and Holloway, 2019; Hansen, 2020; Vik *et al*., 2019). In order to identify the benefits and challenges of PLF in relation to animal welfare (and beyond) and how to address them, a major one-day online workshop gathering over 70 international animal welfare experts, policy-makers, NGO, students, farmers and industry staff was held in November 2020. A series of presentations and activities allowed the participants to discuss current developments in PLF for several species, their potential benefits to welfare, as well as the challenges and potential solutions. In this commentary, we focus specifically on the challenges and risks of PLF raised in this workshop and highlight areas for further research. These are summarised in Figure 1 and discussed below.

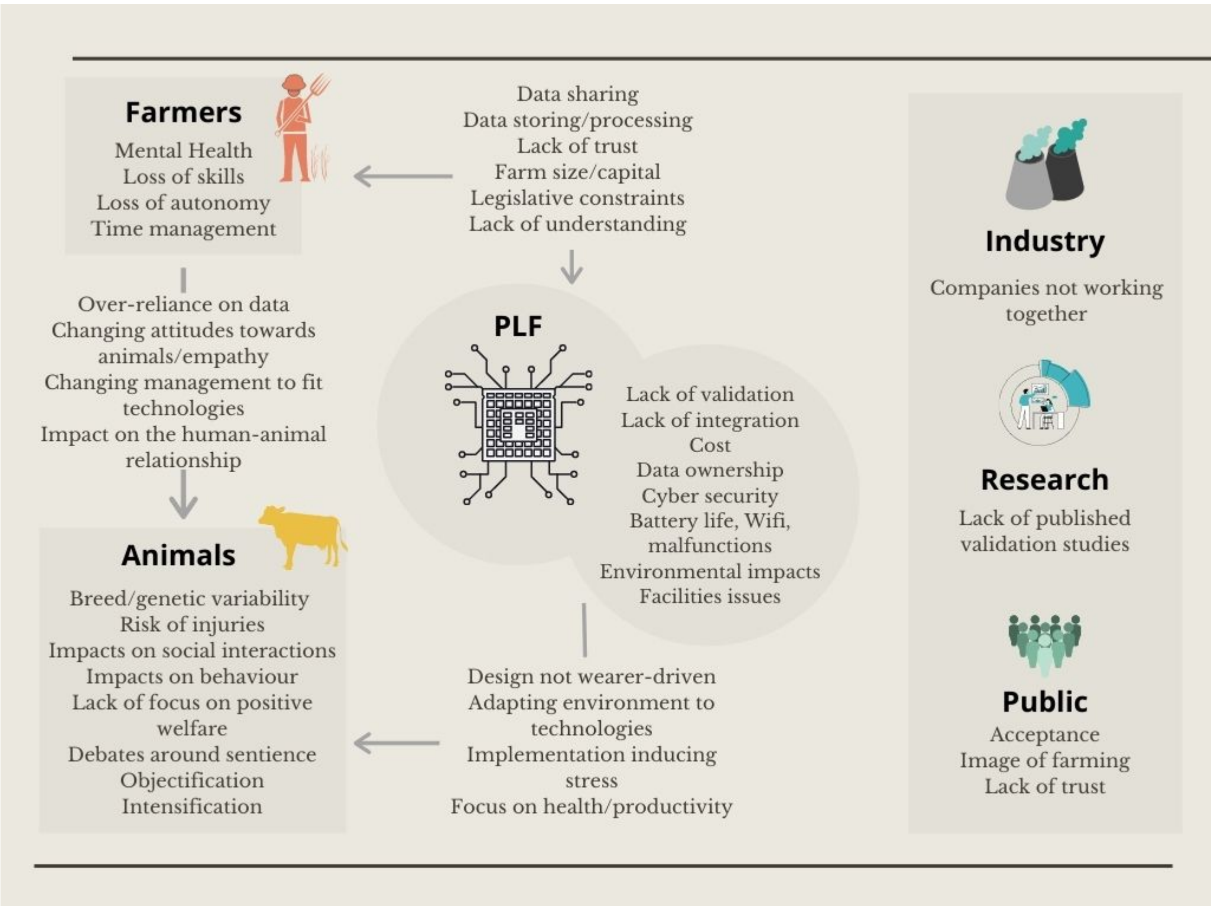

Figure 1: A summary of the risks and challenges of Precision Livestock Farming technologies raised in the workshop

1. Technical limitations of PLF technologies

In terms of technical limitations, the validation of PLF technologies was one of the main issues identified during the workshop. Technology validation is required to demonstrate that a system can meet its targets under realistic operating conditions. In the case of livestock farming where many variables must be taken into account, this means that the technology should be validated in different environments and conditions. Issues such as weather or the location of animals may make data collection difficult (especially in extensive systems), as can internet access in rural locations. More generally, there are issues such as limited battery life or the structure of buildings which may not always be suited to the use of PLF technologies (e.g., difficulties to install cameras or the presence of flies and dirty/wet conditions which could impact efficiency). Another important challenge relates to data integration. Thus far, most commercialised technologies operate 'individually' and do not communicate with each other. This means that each technology generates data relating to a specific parameter, which when accumulated could make it difficult for farmers to interpret and make effective decisions based on those different results. Thus, more work is needed to demonstrate to farmers that the 'promise' of precision actually translates into practice (Kuch *et al*., 2020; Miles, 2019).

2. Challenges for farmers

In the workshop, participants were concerned that many PLF technologies required significant investment from farmers, specialist knowledge and skills to operate or interpret data, advisory support (e.g., from veterinarians), and suitable farm infrastructure (e.g., broadband connectivity). Initial research has suggested that robotic milking technologies have tended to favour larger farms with the capacity both to invest (Yang *et al*., 2021) and access support. Studies focusing on the adoption of general smart farming technologies acknowledge the importance of the factors raised above (Fielke *et al*., 2020; Klerkx *et al*., 2019), as well as that of trust, which workshop participants also raised. Lack of farmer or advisor trust in the technologies may be linked to a lack of validation as well as information relating to cost-effectiveness. It may also relate to questions surrounding data ownership and how the data is used and stored, and who is able to access it (Wiseman *et al.*, 2019). This may in turn cause feelings of vulnerability, especially where cameras are working continuously. As large amounts of data are often stored on 'clouds', there are also concerns surrounding cyber security.

Workshop participants also raised questions about potential impacts on farmers' mental health linked to productivity and pressure to keep up with key performance indicators. Some farmers may not feel comfortable with the use of new technologies that may be difficult to understand and that require different sets of skills (Barrett and Rose, 2022). Furthermore, there is the chance that PLF decreases animal keepers' contact with their animals, which could lead to negative welfare outcomes (see below), and reduced stockmanship skills (Butler and Holloway, 2016; Werkheiser, 2018). It was questioned whether PLF may also have an impact on farmers' autonomy, making them more dependent on external devices. Technologies could change what it means to be a farmer and make the job less attractive to some (Rose et al., 2018), though we acknowledge they could attract new workers to the industry

3. *Animal welfare challenges*

Workshop participants emphasised the variability in production systems in terms of species, genetic variability and rearing environments, as well as individual variability in behaviours such as feeding or drinking. For this reason, devices that are not 'wearer-driven' or re-purposed for different species may not always be suitable; hence there is a potential that devices could cause physical injuries (e.g., due to the weight of a wearable sensor) or have impacts on animal behaviour (e.g., on social behaviour), especially if a single animal is wearing multiple devices. There are also concerns that the implementation of PLF could change farm management to fit the use of technology rather than to improve welfare. For example, cameras may need longer and brighter light hours to work efficiently, or rearing environments may be made more barren to reduce obstacles or background noises for cameras.

Experts in the workshop pointed out that most PLF technologies appear to focus on productivity and health parameters and that while health is integral to welfare, other aspects (e.g., positive animal welfare) should also be taken into account. We also discussed whether the implementation of PLF would result in farmers spending less time with their animals, which could have an impact on the human-animal relationship and perhaps even change human attitudes towards animals (Butler and Holloway, 2016; Bear and Holloway, 2019). This, in turn, may lead to more ethical challenges such as the objectification of animals and further intensification, as PLF can help farmers monitor larger numbers of animals (Werkhesier, 2018; Miles, 2019).

4. Consumer attitudes

Experts in the workshop argued that consumer acceptance is an important aspect of responsible innovation and successful introduction of technologies (see Siegrist, 2020). When it comes to food, consumers are often concerned about 'naturalness', which is also the case for people's perception of animal welfare (Koyratty *et al.*, 2014; Schuppli *et al.*, 2014). For this reason, workshop participants wondered whether a more digitalised, high-tech, and 'faceless' version of farming would be acceptable to the consumer.

Overcoming the challenges

In our workshop, we also discussed how to address the technical, social, welfare, and consumer challenges raised above. Experts argued that:

- Technologies must be wearer-driven (considering genetic variability, breeds, rearing environment, welfare needs) and co-designed in consultation with multiple stakeholders, including the farmer to improve its on-farm relevance and suitability;
- More funding/research is needed on technology validation; data integration; the added value of PLF; implications for animal welfare (assessment parameters, positive welfare, benefits of PLF); consumer acceptance; and farmer engagement;
- A code of practice is needed, developed in collaboration with farmers on data ownership/storing/sharing/privacy, to increase transparency and trust;
- We need to engage with other stakeholders: consumers, veterinarians, milk buyers, retailers, etc. at an early stage: educate, raise awareness and promote discussion;
- Accessible (cost, location, appropriate format) training needs to be provided to farmers to facilitate use of technologies and ensure technical assistance is provided;
- Support is needed to enable farmers to adopt technologies, including rural infrastructure, incentives to adopt, and advisory support.

We argue that whilst further efforts are needed to improve the scientific sophistication of PLF technologies, the research community, policy-makers, and funders alike need to place a greater emphasis on the ethical implications of their use. This will require a trans-disciplinary effort and a systems perspective, involving farmers, advisors, researchers and technologists in co-creation, rather than relying on 'technology push'.

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Appendix 3: Survey Questionnaire

Please provide a **code-word** below if you would like to retain the right to withdraw your data after submission. You will need to provide us with the code-word for us to be able to identify your data and delete it.

____

Q1. What is your age category?

- ☐ 18 - 24
- ☐ 25 - 34
- ☐ 35 - 44
- ☐ 45 - 54
- ☐ 55 - 64
- ☐ 65 - 74
- ☐ 75 - 84
- ☐ 85 or above

Q2. What is your role on the farm?

- ☐ Registered business owner (land owner)
- ☐ Registered business owner (tenant)
- ☐ Farm manager (not business owner)
- ☐ Herd manager
- ☐ Other (please specify) ______________________

Q3. In which of these regions is your farm located?

- ☐ Greater London
- ☐ South East
- ☐ South West
- ☐ West Midlands
- ☐ North West
- ☐ North East
- ☐ Yorkshire and the Humber
- ☐ East Midlands
- ☐ East of England
- ☐ Wales
- ☐ Scotland
- ☐ Northern Ireland

Q4. How many years of experience do you have in dairy farming?

- ☐ Less than 5 years
- ☐ Between 6 and 10 years
- ☐ Between 11 and 20 years
- ☐ Between 21 and 30 years
- ☐ Over 30 years

Q5. What is your herd size (12 months rolling herd size to include calved heifers and cows - do not include youngstock)?

Q6. What type of milking system do you use?

- ☐ Conventional milking parlour
- ☐ Automated Milking System (robot milking)

Q7. How many full-time employees are working on your dairy enterprise (including you and/or family)?

Q8. How many part-time and/or casual employees are working on your dairy?

Q9. What type of grazing system are you operating?

☐ Housed all year round

☐ Grazed all year round

☐ Both housed and grazing periods (please indicate how many months cows are grazed per year)

In this survey, **Precision Livestock Farming** (PLF) technologies include devices such as sensors, cameras, microphones or boluses. More generally, PLF technologies are used on or around animals to help farmers monitor aspects of animal productivity, animal health and welfare or the environment, automatically and continuously.

Examples: sensors for heat detection, activity, feeding, productivity, cameras to monitor lameness or feeding, boluses to monitor rumen health, etc.

Q10. Please select which statement best describes your current situation in relation to PLF technologies:

☐ I do not currently use PLF technologies and have no intention of doing so
(if selected, please continue at Q30)

☐ I do not use PLF technologies at the moment, but I would like to use them in the future
(if selected, please continue at Q28)

☐ I am in the process of implementing one or more PLF technologies
(if selected, please continue from Q11 to Q13, then from Q23 to end of survey)

☐ I am currently using one or more PLF technologies
(if selected, please continue at Q11)

Q11. Which of the following parameters are you currently (or in the process of) monitoring using Precision Livestock Farming (PLF) technologies on your farm?

Please tick all that apply with the associated technology type.

	On-animal (wearable) sensors	Other Sensors	Camera	Bolus	Sound	Parlour/robot
Activity *(including lying and standing)*	☐	☐	☐	☐	☐	☐
Body condition	☐	☐	☐	☐	☐	☐
Body weight	☐	☐	☐	☐	☐	☐
Calving	☐	☐	☐	☐	☐	☐
Drinking behaviour	☐	☐	☐	☐	☐	☐
Environmental parameters *(temperature, ventilation...)*	☐	☐	☐	☐	☐	☐
Feeding behaviour	☐	☐	☐	☐	☐	☐
Heat	☐	☐	☐	☐	☐	☐
Lameness	☐	☐	☐	☐	☐	☐
Location	☐	☐	☐	☐	☐	☐
Mastitis	☐	☐	☐	☐	☐	☐
Methane emissions	☐	☐	☐	☐	☐	☐
Milk yield	☐	☐	☐	☐	☐	☐
Physiology *(pH, temperature...)*	☐	☐	☐	☐	☐	☐
Rumination	☐	☐	☐	☐	☐	☐
Other parameters *(please specify)*	☐	☐	☐	☐	☐	☐

Q12. If you would like to add any further details to the table above regarding the technologies you are using, please describe them below.

Q13. Please indicate how important the following factors were in your decision to adopt PLF technologies:

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
Effects on productivity	☐	☐	☐	☐	☐
Health management	☐	☐	☐	☐	☐
Welfare management	☐	☐	☐	☐	☐
Ease of use	☐	☐	☐	☐	☐
Ease of installation	☐	☐	☐	☐	☐
Cost of installation	☐	☐	☐	☐	☐
Support available	☐	☐	☐	☐	☐
Address labour issues	☐	☐	☐	☐	☐
Lifestyle benefit	☐	☐	☐	☐	☐
Recommendation by advisors/peers	☐	☐	☐	☐	☐
Environmental benefits	☐	☐	☐	☐	☐
Other (*please specify*)	☐	☐	☐	☐	☐

Q14. What kind of changes to your farm management routines resulted from the use of PLF technologies, if any?

	No changes	Minor changes	Major changes
Routine tasks	☐	☐	☐
Work schedule	☐	☐	☐
Number of full-time staff	☐	☐	☐
Number of part-time/casual staff	☐	☐	☐

Time spent on digital devices (computers, tablets, phones)	☐	☐	☐
Time spent with animals	☐	☐	☐
Other (*please specify*)	☐	☐	☐

Q15. How much do you or your staff rely on PLF technologies to monitor your herd in comparison to visual or manual monitoring, across all management tasks?

Please cross the bar under the appropriate percentage. For example, if you rely on technology and manual monitoring equally, cross the bar under '50'.

Not relying on PLF at all					50/50					Complete reliance on PLF
0	10	20	30	40	50	60	70	80	90	100%

Q16. How often do you manually or visually verify whether the data collected by the technologies are accurate? *In the case of heat detection for example, by looking for additional, visual signs of cows in heat.*

☐ Never
☐ Sometimes
☐ About half the time
☐ Most of the time
☐ Always

Q17. How has the time spent visually or manually assessing the health and welfare of your herd changed since the implementation of PLF technologies?

☐ Substantially decreased
☐ Somewhat decreased
☐ About the same
☐ Somewhat increased
☐ Significantly increased

Q18. How has human contact with the cows in the herd changed since the implementation of PLF technologies?

☐ Substantially decreased
☐ Somewhat decreased
☐ About the same
☐ Somewhat increased
☐ Significantly increased

Q19. In your opinion, how is the relationship between stockpeople and the herd since the implementation of the technology?

☐ Much worse
☐ Somewhat worse
☐ About the same
☐ Somewhat better
☐ Much better

Q20. How did the technologies affect the parameters they are designed to monitor?

For example, improved reproduction with heat detection or reduction of lameness prevalence in the case of automatic lameness monitoring.

	Much worse	Somewhat worse	About the same	Somewhat better	Much better
Technology 1: _______________ (*Please indicate which technology you are referring to*)	☐	☐	☐	☐	☐
Technology 2: ________________	☐	☐	☐	☐	☐
Technology 3: ________________	☐	☐	☐	☐	☐
Technology 4: ________________	☐	☐	☐	☐	☐
Technology 5: ________________	☐	☐	☐	☐	☐

Q21. In your opinion, how has the welfare of animals in your herd changed due to the implementation of PLF technologies?

☐ Much worse

☐ Somewhat worse

☐ About the same

☐ Somewhat better

☐ Much better

Q22. In your opinion, how has the behaviour of your livestock changed since the implementation of PLF technologies?

	They are more...	They are less...	No change
Relaxed	☐	☐	☐
Calm	☐	☐	☐
Content	☐	☐	☐
Friendly	☐	☐	☐
Nervous	☐	☐	☐
Indifferent	☐	☐	☐
Distressed	☐	☐	☐
Uneasy	☐	☐	☐

Q23. In your opinion, how effective was the training you have received to efficiently use the technology?

☐ Not effective at all
☐ Slightly effective
☐ Moderately effective
☐ Very effective
☐ Extremely effective
☐ Not applicable

Q24. What kind of challenges, if any, have you encountered during the implementation of PLF technologies on your farm?

Q25. If you have encountered any challenges, please describe whether these have been overcome and if so, how?

Q26. If you have encountered any challenges, how have they affected your attitudes towards the technologies?

☐ Very negative impact
☐ Slightly negative impact
☐ No impact
☐ Slightly positive impact
☐ Very positive impact
☐ Not applicable

Q27. To what extent do you agree with the following statements in relation to PLF technologies on your farm?

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree	Not applicable
I was able to provide feedback to technology providers	☐	☐	☐	☐	☐	☐
Technology providers have helped me interpret the data efficiently	☐	☐	☐	☐	☐	☐
Technology providers are transparent regarding ownership and use of data	☐	☐	☐	☐	☐	☐
I believe my feedback is taken into account in the development of the technologies	☐	☐	☐	☐	☐	☐
Challenges met during implementation have been actively addressed by the technology providers	☐	☐	☐	☐	☐	☐

Q28. What has prevented you from implementing PLF technologies on your farm so far? *Please provide examples where possible.*

Q29. Which types of PLF technologies would you like to implement in the future and why?

Q30. What are the reasons why you do not wish to implement PLF technologies on your farm?

Q31. Would you like to be contacted for a follow-up interview on this topic? If so, please provide your email address below. If you do not wish to take part in further study, please leave blank.
Please note that we may not be able to contact all people who leave an address, however, we will send summary results towards the end of the study if you do.

Q32. Do you have any further comments?

Appendix 4: Topic guide example

1. Introduction

- Introduce PhD topic
- Overall aims of the study
- Confidentiality reminder
- Recording and length of interview
- Check for questions prior to start

2. General information
Aims: Background - how participants got involved in the project

- Details about current role
- Start date - involvement in the project
- Aims of the project/describe technology/what it is for
- Reasons for being involved

3. Experience with technology
Aims: To discuss general adoption factors and attitudes towards technology (general and focused on the technology)

- Describing experience with the technology

◊ Start and frequency of use
◊ Experience of implementation
◊ How is the data used? By whom?
◊ General impressions/attitudes (performance, ease of use, relevance…)
◊ Key factors for technology adoption

4. Participation
Aims: To uncover first aspects of participation in technology development and implementation

- Involvement experience

◊ Extent of participation/examples

- Facilitating conditions

◊ Communication with other stakeholders
◊ Ability to provide feedback
◊ Feedback consideration/action
◊ Availability of training and support – efficiency

- Challenges

◊ Type of challenges met
◊ Have they been overcome and how

- Impacts

◊ Benefits
◊ Drawbacks

- ◊ Attitudes towards the technology
- ◊ Technology use as a result of participation
- ◊ What have they learned

If **not**:

- ◊ Would they have liked to be involved and how?

- Factors encouraging or affecting use in the long term

5. Impact on management and welfare

Aims: Views on the impact of the technology on learning, management, and welfare

- Attitudes to technology
- ◊ Attitudes towards the method
- ◊ Attitudes towards practicalities/applying the technology

- Potential of the technology to promote learning
- ◊ What have they learnt about welfare
- ◊ Impact on perception understanding/knowledge of animal behaviour and welfare
- ◊ Potential for changes to welfare management
- ◊ Changes in attitudes since using the technology
- ◊ New skills acquired since the use of the technology
- ◊ Are they doing anything differently?

6. Assurance schemes

Aims: Uncovering stakeholders' perception of the use of DLTs by farm assurance schemes/retailers

- ◊ What is the value of the technology
- ◊ Thoughts about use of technology for assurance purposes
- ◊ Enabling factors for successful use
- ◊ What are the potential barriers

7. Future

Aims: Finding out views about the future of PLF and the wider impacts

- ◊ Use of the technology within the wider industry
- ◊ General impacts on stakeholders (farmers, consumers…)
- ◊ General impacts on animal welfare
- ◊ Any other questions

8. Conclusion

Aims: Reminding confidentiality and other aspects

- ◊ Thanks
- ◊ Confidentiality
- ◊ Contact if needed