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Designing precision livestock farming system innovations: A farmer perspective

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ABSTRACT

Precision livestock farming (PLF) is increasingly being suggested as a promising tool for contributing to the sustainable transition of livestock farming as a market system innovation for farm-animal value chains. The innovations of PLF systems are over and above applications aimed at achieving on-farm goals (*e.g.* improving efficiency and monitoring farm animals), which are well recognised in the existing literature. This paper specifies the new dimensions of PLF systems, including data-sharing with retailers in the chain, with certifiers/control organisations, with other farmers and with market innovators, as well as data governance. Because farmers approach PLF applications that extend beyond on-farm use with reluctance, it is crucial to take farmer preferences into account when designing multi-actor PLF-system innovations. Proceeding from a mixed-method design, this study begins with a literature review and expert interviews, followed by an examination of farmer preferences regarding the architectural-design attributes of a PLF-system innovation. The latter takes the form of a conjoint study based on data obtained from 367 pig and dairy farmers in Finland, the Netherlands and Spain. Results indicate that farmers attach the greatest importance to the governing structure that manages their data, followed by the opportunity to use an on-farm early-warning system to monitor farm animals, and the possibility of sharing the collected data with value-chain actors mainly for purposes of optimising business innovation and certification. A cluster analysis further highlights the importance of finding customised solutions, considering the heterogenous preferences of farmers for PLF-system innovations beyond European borders. These preferences should be considered in the design of multi-actor PLF-system innovations.

1. Introduction

While agriculture in general and animal-based sectors in particular are under pressure to adopt more sustainable and animal-friendly ways of producing food, new technologies are emerging that could help the agricultural sector accomplish a sustainable transition (Geels, 2019). The advent of Industry 4.0, cloud computing, the Internet of Things and innovations in robotics, artificial intelligence and computer vision (Lokhorst et al., 2019) are having a transformational impact on agriculture through the emergence of new agriculture-specific technologies. One such technology is precision livestock farming (PLF) (Morrone et al., 2022), defined '*as the application of process engineering principles and techniques to livestock farming to automatically monitor, model and manage animal production*' (Tullo et al., 2019). The real-time monitoring and generation of large amounts of on-farm data allow for the development of early-warning systems (Berckmans et al., 2017) and better decisions regarding animal health, welfare, production and reproduction (Rojo-Gimeno et al., 2019), in addition to enhancing farm efficiency (Aquilani et al., 2022; Stygar et al., 2022).

The potential impact of PLF data is however not restricted to the farm level. When shared with and acted upon by other actors within the value chain, such data could also promote the transformation of wider socio-economic networks within which farmers are embedded (Buller et al., 2020; Geels, 2019). At the aggregate level, therefore, PLF-data can be used to identify trends and changes in livestock production, to support decision-making in value chains, to replace on-farm assessments of compliance with farm standards, to assess the impact of policies and interventions, and to support knowledge-sharing. All these ideas are

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consistent with emerging positions on food system innovations (Klerkx and Rose, 2020) and value creation in business ecosystems, orchestration and service networks (Dhanaraj and Parkhe, 2006; Vargo and Lusch, 2016; Valkokari et al., 2017). In this study, therefore, we refer to these multi-actor innovations as *PLF-system innovations*, defined as data-sharing systems between farmers, value-chain actors, governments and civil society that collectively generate technological, social and institutional innovations to reshape the sustainable future of livestock farming.

Existing research on PLF focuses primarily on on-farm applications (*e.g.* Morrone et al., 2022; Aquilani et al., 2022). Notably, authors have also started to explore the first steps towards system innovations, including the engagement of value-chain actors in the innovation process (Eastwood et al., 2019), the grasping of market and technological readiness of PLF innovations (Rijswijk et al., 2019), and the examination of farmers' willingness to share their PLF data (Zhang et al., 2021). Scholars have also expressed a need for a more holistic value-chain perspective on PLF innovations (Rijswijk et al., 2021) and the examination of opportunities stemming from PLF that extend beyond the farm (Buller et al., 2020; Klerkx et al., 2019). We respond to these calls by looking at PLF-system innovations from the perspective of farmer-centric design. The main reason is that, as the primary source of PLF data, farmers constitute the basis for PLF-system innovations and are positioned to either '*make or break*' them (Klerkx et al., 2019). Our study on farmers thus advances research on shaping PLF-system innovations without ignoring the role of other stakeholders.

More specifically, our study explores questions concerning (1) the dimensions that PLF-system innovations add to the existing on-farm use of PLF data; (2) the attributes of PLF-system innovations that farmers prefer; (3) the possible influence of sectoral and country-specific differences on such preferences; and (4) the optimal arrangement of attribute levels for farmers in a newly designed PLF-system innovation. Following the design perspective (*e.g.* Löwgren and Stolterman, 2004), we start by identifying the most important attributes of PLF-system innovations through a survey of relevant literature and information obtained from 45 expert interviews in five European countries. The insights from this preliminary study were used as the foundation for a quantitative conjoint experiment (cf. *for comparable methodological approaches:* Green and Srinivasan, 1990; Aramyan et al., 2013; Hounhouigan et al., 2014) involving 367 pig and dairy farmers from the Netherlands, Finland and Spain. The experiment investigated the importance that actors attach to different attributes, as well as their preferences for specific attribute levels. Conjoint analysis has the potential to provide insight into the attributes that farmers consider important and the levels that they prefer, thereby offering concrete insight into the architectural design of PLF-system innovations.

The findings of our study contribute to previous research in three ways. First, our results contribute to the '*designability*' of PLF-system innovations by identifying their key architectural-design attributes. In this respect, our research responds to calls to study farmers' perceptions and characteristics more holistically and inclusively, as well as to provide relatively tangible outcomes to these calls (*e.g.* Rijswijk et al., 2021; Klerkx et al., 2019). Second, our study contributes to the specific understanding of the preferences of farmers concerning the digitalisation of livestock farming (Fielke et al., 2020; Rotz et al., 2019) by capturing the valence of preferences in relation to the farm, chain and legal environment. In this way, we adopt a holistic farm-centred approach to explore farmer preferences for PLF-system innovations within the wider context in which they are operating. Third, our study has empirical and practical implications that support the implementation of PLF-system innovations to foster the creation of farmer-centric, digital business ecosystems as '*networks of practice*' (Oreszczyn et al., 2010), thereby contributing to the digital, sustainable transition of the livestock sector.

The remainder of this paper begins by identifying the attributes of PLF system innovations pertaining to the value chain, institutional environment and farm by drawing on literature and expert interviews. We then present the methods applied in the quantitative conjoint study, followed by a presentation and discussion of the results. The article finishes with implications and a conclusive remark.

2. Identifying the attributes of PLF-system innovations

Given the complex nature of PLF systems, they have the potential to influence farmers in many different ways. To identify the most important architectural-design attributes and attribute levels of PLF-system innovations, we explored the relevant literature and conducted interviews with 45 experts who were either directly or indirectly affected by PLF-system innovations, covering the entire livestock value chain of pigs and dairy production. The two agricultural sectors were selected because the integration of PLF is seen as a driver of innovation in both sectors (*e.g.*, Tzanidakis et al., 2021; Lovarelli et al., 2020). Currently, PLF is used in the dairy industry for system automation, disease detection, performance and feeding monitoring as well as animal behaviour observation (Lovarelli et al., 2020). Although PLF is currently less common in the pig sector, it is still used to detect diseases and to measure animal performance, feed intake and behaviour (Morrone et al., 2022; Tzanidakis et al., 2021). Consequently, experts included dairy cow and pig farmers, representatives of farmer cooperatives and slaughterhouses, as well as food processors, retailers, technology providers (both hardware and software), consultants, researchers and animal-interest-groups were recruited for this study. Informants were selected from five European countries (Finland, Sweden, the Netherlands, Italy and Spain). A description of participants is included in Appendix 1. The results of the interviews were used to verify the results derived from the literature review, thus enhancing validity and potentially offering additional attributes or attribute levels (or arguments and insights on which they are based), from practice that have yet to be reflected in the literature.

The attributes and attribute levels are listed in Table 1, along with representative references. Attributes are grouped along the lines of the value-chain environments of which the farmers are part: the on-farm use of PLF data, the governance of PLF data and the sharing of PLF data within the value-chain environment. Given that the on-farm use of PLF data has been dealt with extensively in previous studies, we discuss attributes pertaining to the value chain and institutional environment first. Moreover, because the number of attributes that can be included in a conjoint analysis is limited (Green and Srinivasan, 1990), we focus on the most important ones, grouping more specific attributes together wherever possible. We also tried to identify the attributes that were still surrounded by some ambiguity, in that they entail both advantages and disadvantages for farmers, such that the preferences of farmers are far from obvious. The results led to the identification of seven attributes and attribute levels.

2.1. PLF data-sharing within the value chain

The bottom-line argument for PLF-system innovations is that, when aggregated data are pooled across many farms within a digital ecosystem, they can reveal previously undiscovered patterns and insights that would be impossible to identify when examining only PLF data from individual farms (Coble et al., 2018). Studies by Fielke et al. (2020) and by Marvin et al. (2022) have recently drawn attention to data-sharing within the value chain (*e.g.* with other farmers, input suppliers, buyers and intermediaries). The sharing of data within this context is thus expected to foster the exchange of other information, in addition to making the chain more transparent, whilst promoting trust and accountability (Zhang et al., 2021; Schillings et al., 2023a).

(1) Data-sharing with farmers to benchmark farm performance. Sharing data with other farmers is probably the simplest and safest form in which farmers can contribute to and benefit from PLF-system innovations. According to Zhang et al. (2017), farmers are generally

Table 1
Attributes and alternative levels of PLF-system innovations examined in this study, along with their expected risks and benefits.

	Attributes	Levels	References
2.1 Data-sharing in the value chain	Data-sharing with farmers to benchmark farm performance (1): System shares data with other farmers, thereby allowing farmers can benchmark their performance.	Present Not present	• Fielke et al. (2020) • Marvin et al. (2022) • Zhang et al. (2021) • Schillings et al. (2023a) • Knierim et al. (2018)
	Data-sharing with control and certification organisations (2): System shares data with monitoring, control and certification organisations to reduce the costs of monitoring, control and certification costs, as well as to increase transparency.	Present Not present	• Benjamin and Yik (2019) • Tonkin et al. (2016) • Anneberg et al. (2012) • Escobar and Demeritt (2017)
	Data sharing with retailers (3): System allows feedback from retailers to help farmers to improve production and respond to customer demand.	Present Not present	• Schulze et al. (2019) • Binnekamp and Ingenbleek (2006) •
	Data-sharing with market innovators (4): System shares the data with companies (*e.g.* specialty stores, innovative processors and restaurants) to enhance product branding and creation of new business models.	Present Not present	Stygar et al. (2022) Schillings et al. (2023a) Lu et al. (2020) Poppe et al. (2015)
2.2 Data governance	Governing organisation (5): The board of the organisation may consist of … representatives safeguarding data, as well as managing and validating the data.	A farmers' organisation A retailer consortium A multi-stakeholder consortium	• Jayashankar et al. (2018) • Wiseman et al., 2018 • Kaur et al. (2022) • Astill et al. (2020) • Ingenbleek and Immink, 2010
2.3 On-farm use of PLF data	Data-driven monitoring (6): System monitors feed intake, environmental impact and use of antibiotics and other medicine per animal head.	Present Not present	• Morrone et al. (2022) • Hartung et a., 2017 • Norton and Berckmans (2017) • Vranken et al. (2017)
	Early warning systems (7): System sends a warning signal when one or more of the indicators for animal health or welfare deviates from the norm.	Present Not present	• Hostiou et al. (2017) • Bianchi et al. (2022) • Berckmans et al. (2017)

open to sharing their data with other farmers within the value chain networks they operate. Farmers are likely to do so because it allows them to compare their performance with farms operating in comparable markets. Sharing data with peers can also facilitate communication around common issues, thereby allowing stakeholders to collaborate and co-learn (Schillings et al., 2023b). This can enhance the technical and financial efficiency of livestock farming. For example, Ramsbottom et al. (2021) report a positive correlation between the frequency of financial benchmarking and farming efficiency. In addition, farmers tend to trust and reciprocate with their peers more and perceive a lower risk of exploitation, as compared to their non-farmer counterparts (Knierim et al., 2018; Zhang et al., 2021). However, data sharing is highly dependent on the circumstances. The willingness to share data is influenced by the perception of who is the main beneficiary (Zhang et al., 2021). Thus, perceived benefits and lack of trust hinder the sharing of data by farmers. For this reason, we include the *sharing of data with farmers to benchmark individual performance* (present or not) as an important attribute of PLF-system innovations.

(2) Data-sharing with control and certification organisations. Sharing data with control and certification organisations can reduce costs, as it reduces the frequency of 'in-person' farm audits (Benjamin and Yik, 2019). It can also promote trust between farmers and buyers, as PLF-based control can be continuous and therefore more reliable than farm audits, which are announced in advance (Tonkin et al., 2016). In addition, PLF data can validate new farm practices and systems of which the impact on animals and environment is still uncertain (Higgins et al., 2008). Farmers may nevertheless regard monitoring, certification and control as necessary '*evils*' (Anneberg et al., 2012). When control or certification are mandated by powerful players in the chain, such power differences could also affect the attitudes of farmers towards auditors, thereby leading to distrust (Escobar and Demeritt, 2017). For this reason, we include the *data-sharing with control and certification organisations* (present or not) as a second design attribute of PLF-system innovations.

(3) Data-sharing with retailers. Food retailers play a crucial role in the distribution of farm-animal products that have been produced under higher animal-welfare standards (Schulze et al., 2019). The strategic position of food retailers within the value chain — between suppliers (*e.g.* farmers and processors) and end-consumers — grants them control over the flow of goods, information and value creation. The ownership of PLF data reinforces the market and value-chain position of farmers, however, as it enables them to demonstrate evidence of their sustainable practices (*e.g.* objective representation of the health and welfare of farm animals). In their turn, retailers can also benefit from PLF data, which allow them to objectively assess whether the products they have listed align with expressed or demonstrated consumer demands and behaviours for more sustainable and animal-friendly husbandry practices. Despite the individual or mutual benefits to farmers and retailers, several points of friction and possible barriers that influence the exchange of PLF data between these parties have been identified. For example, the power position of retailers, price competition on the market, and the price orientation of decision-makers have been identified as potential market barriers for product innovations aimed at enhancing animal welfare (Binnekamp and Ingenbleek, 2006), including products produced through PLF-system innovations.

Farmers may also harbour concerns that their business partners will exploit the data they have shared to enhance their own performance without providing them with any direct *quid pro quo*. Through PLF-system innovations, retailers have the opportunity to enhance their sustainability and welfare ratings by prioritizing the highest-scoring farmers as their preferred suppliers. Another implication of this approach, however, is that farmers with the lowest scores could face closure unless immediate action is taken to meet the requirements set by the retailing partner. Farmers may therefore be reluctant to share their data with downstream trading partners (*e.g.* retailers), for fear of strengthening the retailers' position of power and weakening their own positions. This reluctance could be mitigated by establishing a well-defined, mutually advantageous agreement that addresses risks for farmers and guarantees reciprocal benefits amongst all participants in the value chain. The act of sharing data with retailers is consequently regarded as an indispensable attribute, including with regard to the transition of livestock farming towards sustainability. In the present study, therefore, it is explored as the third attribute of PLF-system innovations.

(4) Data-sharing with market innovators. One step further than the use of PLF data to optimise '*business as usual*' entails drawing insights from the data that could lead to market innovations within the chain. Because PLF can be used to justify product claims (Stygar et al., 2022), PLF data can present opportunities to identify and access new market segments. For example, by providing information on production activities, PLF data could open access to customer segments that value products that have been produced in a transparent way (Schillings et al., 2023a). When companies identify market segments comprising consumers who are willing to pay more for offering produced with PLF (Lu et al., 2020), they can take these products out of the mainstream and market them under specific brands, labels and/or specialty stores or restaurants. This could create value for market segments that may have a high level of interest in animal welfare, sustainability and/or local or regional livestock production (Poppe et al., 2015). The vertical integration of reliable, valid and objective PLF information into the value chain could thus open new markets, revenue streams and channels, thereby allowing farmers and innovators to grow into new markets by developing innovative PLF offerings.

The possibilities are nearly endless. They could even extend to consumers who are looking for specific characteristics of their animal produce and finding them in specific nearby farms, which then further specialise to respond to the preferences of these consumers. For example, in the dairy sector, the Lely company is already anticipating this situation by providing farmers with small milk-processing plants on their farm, thereby enabling them to take care of their own marketing and adjust their farm practices to the preferences of their local consumers (Lely, 2023). When farmers take more control over their own marketing activities and are more capable of communicating sustainability messages to consumers — because they have stronger personal ties to them — market innovation could have a transformational role in the sector. For this reason, the current study includes *data-sharing with business innovators* as a fourth design attribute.

2.2. Data governance

Data governance is critical to the integration of PLF technologies, but it is also complex and goes beyond commonly discussed issues such as the associated costs of integration, evolving technologies and the lack of robust national and international standards and policy frameworks (Buller et al., 2020). One of the most important issues is the discussion of data ownership, whereby the question of who owns and controls the generated data is controversially discussed and depends on the perspective of the stakeholders involved (Favour et al., 2024). In addition, the potential role of governmental surveillance in accessing data transmitted over national networks raises significant privacy and ethical concerns, making data management a multi-layered challenge in PLF systems. All of this shows that it is imperative to define who is managing PLF data in PLF-system innovations.

(5) Governing organisation. The risk that other players in the system will abuse data shared by farmers is of crucial importance to the acceptance of PLF-system innovations by farmers (Jayashankar et al., 2018). This concern is particularly relevant in the absence of data agreements (Kaur et al., 2022). The issue of data governance has thus been identified as prominent within the context of data-enabled PLF-system innovations (Astill et al., 2020). Data governance encompasses the technical system, processes and strategies that ensure that data can effectively serve their intended purpose, whilst also incorporating aspects of privacy and security, which are highly valued by farmers. During our interviews, several respondents referred to tasks that require a certain level of organisation (*e.g.* converting PLF data into a suitable format for users, pooling data, developing interfaces, securing privacy and preventing hacking).

The sharing and management of data in PLF-system innovations undoubtedly requires some level of organisation and governance. One important question in this regard was raised in the expert interviews: Who will oversee PLF system innovations? The answer to this question is not obvious.

From a farmer-centric standpoint, three potential scenarios emerge. First, as data owners, farmers have the option to designate their own representatives to coordinate the process. Second, data governance could align with established power norms within the value chain, in which dominant entities exert influence, thus compelling less influential suppliers to comply. This arrangement might position retailers at the helm, potentially delegating operational intricacies to other value-chain participants in a manner akin to the decision-making model presented in GLOBALG.A.P. (Ingenbleek and Immink, 2010). Third, decision-making might occur within the framework of a roundtable or a multi-stakeholder platform, involving all value-chain collaborators and external stakeholders. As such, we introduce a design aspect focused on a governance structure denoting three levels of lead organisers in PLF-system innovations: farmer representatives, retailer delegates and a multi-stakeholder platform.

2.3. On-farm use of PLF data

Given that PLF initially emerged as a tool for making data-based improvements on the farm, we complete our model with two on-farm attributes that have been explored extensively in recent research. Again, from a farmer-centric perspective, the inclusion of these attributes is important, as they facilitate the assessment of the relative importance of system-level attributes, as compared to attributes that are already available to farmers in existing applications of PLF.

(6*) Data-driven monitoring.* By connecting farming practices to the continuous, real-time monitoring of farm-animal parameters, PLF allows farmers to monitor the health and welfare status of their animals (Morrone et al., 2022). Farmers can monitor livestock from more in-depth information for better-informed on-farm management decisions. Monitoring has therefore been suggested as important to the improvement of farm performance (Hartung et al., 2017), whilst also contributing to wider societal debates about sustainable livestock farming (Morrone et al., 2022).

(7) Early warning systems go even a step further than the monitoring function of PLF systems, as they can detect the initial signs of deviation from established norms (Norton and Berckmans, 2017; Vranken et al., 2017), thereby anticipating issues relating to health or welfare (Hostiou et al., 2017). The associated reduction of workload and optimisation could in turn motivate farmers to adopt PLF-system innovations (Bianchi et al., 2022). Another advantage of early warning systems is that they rely on autonomic algorithms, and they therefore do not require farmers to possess any additional technological knowledge, skills or capabilities in order to analyse the raw PLF data (Berckmans et al., 2017). We therefore expect that it is crucial to explore the contribution of the two on-farm attributes to the PLF-system innovation.

3. Method

3.1. Data collection

We conducted a conjoint study (Green and Rao, 1971) to arrive at a quantitative assessment of how farmers perceive the importance of the various attributes and to explore their preferred level of these attributes. We invited pig and dairy farmers from Finland, the Netherlands and Spain to complete an online conjoint-analysis questionnaire. These European countries were selected because they differ in their market environment, access to resources, equipment and technologies use, social norms, values and finally their competencies (Huttunen, 2019). While the Netherlands is an exporting country with relatively large and technologically advanced farms, Finland is an EU country with advanced technology in its operations, but for a smaller and more domestic market. Spain, on the other hand, has a more traditional and quality-orientated production sector that mainly produces for the domestic market. In addition, all three European countries were part of the EU-funded ClearFarm project, allowing farmers to participate without additional transaction costs. Only farmers who were currently active were eligible to participate in the study. No additional restriction criteria were applied. To overcome the challenges associated with recruiting farmers to participate in questionnaires, we raised awareness concerning the research amongst pig and dairy farmers in the three European countries by publishing press releases describing the study and its project-related background four weeks prior to the start of the study. The press releases were distributed through media channels familiar to pig and dairy farmers (*e.g.* websites and trade journals). They were also sent to farmer organisations and to farmers who had subscribed to a mailing list in order to participate in the European-funded ClearFarm project (www.clearfarm.eu). The press releases were further shared through social media (Twitter [now X], Facebook and LinkedIn). Incentives were offered to farmers with large social networks to post and share information about the study. After completing the data collection and purification process, 114 responses from pig farmers and 253 responses from dairy farmers were available for the data analysis (Table 2).

Table 2 shows the sample demographics and where available EU average values of farmers for comparison. The numbers compare well to the Finnish average age of farmers in the pork and dairy sectors (both being 49 years of age (Stadb, 2024; CBSa, 2024), the age of farmers in the Netherlands (where 71% is aged between 40 and 67; CBSb, 2024), and the age of farmers in Spain (where 70% is above 55 and only 7% below 40; Fructidor, 2024). The relatively small samples from Spain seem to be biased towards younger farmers who were probably more attracted by the subject of the study, while in the other two countries, the sample looks reasonably representative when it comes to age.

3.2. Procedure

The conjoint questionnaire was developed in English and translated into the local languages of the three participating European countries (Finnish, Dutch, Spanish and Catalan). The translated questionnaires were pre-tested to detect irregularities and to ensure that the questions were unambiguous and clear to the participants. Before completing the questionnaire, informed consent was requested from the participants. After participants granted informed consent, a short introduction text was displayed, describing the PLF-system innovation, its attributes and their value levels. Participants were then asked to evaluate different scenario profiles originating from the conjoint design. This was intended to generate information about the participants' preferences with regard to the PLF-system innovation (Cattin and Wittink, 1982). More precisely, after two warm-up profiles, participants were asked to assess 16 scenario profiles and four additional holdout profiles, with each profile displaying a combination of the attribute levels of the PLF-system innovation. Participants were asked to indicate the likelihood that they would participate in the PLF-system innovation on a 10-point Likert scale ranging from '*very unlikely*' to '*very likely*'.

To make the task more realistic, the monthly price that farmers would pay or receive when engaging in the PLF-system innovation were displayed as additional information cues. The prices or financial incentives offered to the participants were determined based on a market analysis of the current pricing of the existing PLF-service provider. The total price/incentive displayed was thereby the sum of the price/incentive ascribed to a given attribute level for each of the 22 conjoint scenario profiles. Prices ranged from receiving €45 as an incentive to provide PLF data to a fee of €50 per month for using the system. Because the price/incentive was calculated from the sum of the individual attribute levels of the profile, the value of the fee/incentive was not integrated into the statistical model as an additional variable. After completing the conjoint design task, participants were asked to answer additional demographic questions regarding their work experience, age, gender, production system and number of farm animals (Table 3).

3.3. Orthogonal design

We adopted a metric conjoint-analysis approach in which participants were required to evaluate a set of PLF-system innovation scenarios consisting of several attributes and attribute levels to explore the relationships amongst them. This approach allowed the individual attributes and attribute levels to be evaluated independently in terms of importance in their entirety. This method is particularly suitable for

Table 2
Demographic characteristics of pig and dairy farmers included in the data analysis in comparison to EU farmer statistics.

Pig farmers	Netherlands			Spain			Finland		
	N (study)	N (%)	European Average	N (study)	N (%)	European Average	N (study)	N (%)	European Average
Respondents	77		ns.	24		ns.	13	ns.	
Age	47.8		51.4*	43.2		51.4*	48.3	51.4*	
Years of experience	28.05		ns.	23.0		ns.	21.01	ns.	
Gender									
Male	71	92.2%		23	95.8%			9	69.2%
Female	5	6.5%		1	4.2%			4	30.8%
Others	1	1.3%		0	0.0%			0	0.0%
Dairy farmers	**Netherlands**			**Spain**			**Finland**		
	N (study)	***N (%)***	***European Average***	***N (study)***	***N (%)***	***European Average***	***N (study)***	***N (%)***	***European Average***
Respondents	183		ns.	41		ns.	29	ns.	
Age	49.4		51.4*	43.9		51.4*	45.0	51.4*	
Years of experience	31.2		ns.	22.0		ns.	21.01	ns.	
Gender									
Male	159	86.9%	94.4%	32	78.0%	71.4%	17	58.6%	89.1%
Female	23	12.6%	5.6%	8	19.5%	28.6%	12	41.4%	10.9%
Others	1	0.5%	ns.	1	2.5%	ns.	0	0.0%	ns.

*for all farmers in the EU.
sig. level $p < .00$.

Table 3
Attribute importance and utility estimates of the system attributes for pig and dairy farmers, including the main effects of the attributes.

	Pig farmers					Dairy farmers				
Attribute and Level (presence)	Relative importance in %	Utility estimate	df	F statistic	P-value	Relative importance in %	Utility estimate	df	F statistic	P-value
A1 Data-sharing with other farmers to benchmark performance	8.73		1	0.76	0.39	8.97		1	0.72	0.40
Present		0.07					0.05			
Not present		0.00					0.00			
A2 **Data-sharing with control & certification organisations**	11.84		1	42.86	0.00	13.51		1	69.84	0.00
Present		0.54					0.45			
Not present		0.00					0.00			
A3 **Data-sharing with retailers**	9.16		1	0.05	0.82	9.90		1	14.79	0.00
Present		0.02					−0.21			
Not present		0.00					0.00			
A4 **Data-sharing with market innovators**	12.00		1	61.76	0.00	12.83		1	201.71	0.00
Present		0.64					0.77			
Not present		0.00					0.00			
A5 **Governing organisation**	31.54		2	164.00	0.00	29.22		2	247.61	0.00
Consist of farmers		0.87					0.72			
Consist of retailers		−0.93					−0.74			
Consist of a multi-stakeholder consortium		0.06					0.02			
A6 **Data-driven monitoring**	15.24		1	45627	0.29	13.27		1	1.09	0.17
Present		0.09					0.074			
Not present		0.00					0.000			
A7 **Early-warning systems**										
Present	12.06	0.53	1	122.34	0.00	13.33	0.60	1	41.46	0.00
Not present		0.00					0.00			
Intercept		4.17					4.03			
Error		5206.13	1702				11214.56	3787		
Correlation coefficients		Values					Values			
Pearson's R		0.987					0.997			
Kendall's tau		0.933					0.950			
Kendall's tau for Holdouts		0.667					1000			

determining the preferences of farmers for the attributes of PLF-system innovations, as well as the levels of these attributes.

Because each of the seven attributes had two or three levels, the full factorial design with all possible combinations of the PLF data system would have generated 192 different profiles: 2 (monitoring system: yes/no) × 2 (warning system: yes/no) × 2 (data access: yes/no) × 2 (data-sharing: yes/no) × 2 (new business opportunities: yes/no) × 2 (feedback system: yes/no) × 3 (governance represented by: farmers/retailers/consortium). This would have been too many scenarios to be evaluated by each respondent. We therefore used SPSS 27 (https://www.ibm.com/products/spss-statistics) to create a fractional-factorial main-effects design, resulting in an orthogonal array with no interaction effects. The orthogonal design had a total of 22 different scenarios, including two warm-up profiles to familiarise participants with the procedure and four hold-out profiles to validate the results retrospectively. Except for the warm-up profiles, the displayed scenarios were presented in a fully randomised manner to cope with common method biases (*e.g.* ordering effects).

3.4. Consistency and validity check

We applied a three-step approach to check the consistency and validity of responses (*cf.* Gocsik, van der Lans, Lansink & Saatkamp, 2016). First, Pearson's R was calculated to analyse the correlation between observed and estimated preferences. Internal validity was tested using the Pearson correlation coefficients between the predicted values for the holdout profiles and their actual observed values for each respondent. Lower Pearson coefficients indicate reduced internal validity. Following this procedure, participants with Pearson's R values < 0.6 were excluded from the data analysis. Second, Kendall's t-values were used to analyse the correlation between the observed and estimated scores of the hold-out profiles. High internal validity is assumed when high values are obtained for Kendall's tau, with $p < .05$. Participants with Kendall's tau values < 0.6 were therefore excluded from the data analysis. Third, participants who evaluated all scenarios (attributes and attribute levels) as equally important were excluded from the analysis, as this suggests inauthentic or thoughtless responses.

3.5. Attribute importance and utility values

The utility of the PLF-system innovation profile was estimated by summing the partial utilities belonging to its attributes (cf. Gocsik et al., 2016). The 'part-worths' of an attribute represent its utility value. Given that part-worths are expressed in common units, they can be added together to give the total utility. Positive utility values are associated with a positive effect of the attribute on the overall value of a scenario profile. The utility values were used to identify the attributes that contributed the most to the utility of a profile. They were also used to determine the relative importance of each attribute. The relative importance of an attribute was derived by comparing the utility range of the attribute to the utility range of all attributes. Relative importance was expressed as a fraction of total importance. Higher values indicate greater importance of attributes within the context of the conjoint design and its attributes.

To test the directions of the effects, we conducted an ANCOVA in SPSS 27 (https://www.ibm.com/products/spss-statistics). Following the approach proposed by Iacobucci et al. (2016), we performed the univariant analysis by calculating the mean-centred scores for each respondent in order to negate individual differences in mean acceptance. The mean-centred scores were computed by subtracting the participants' mean scores from the scores assigned to each of the 16 scenario profiles. The data from all farmers were thus treated as individual values rather than repeated measurements. The attributes of the PLF data system were included as factors, and the associated evaluation scores were included in the model as the dependent variable.

3.6. Cluster analysis

Given our expectation to identify heterogenous preference clusters across and within farmers from the two farming sectors and for the three European countries, we conducted a k-means cluster analysis to classify the observations into homogeneous groups. This was done according to a two-fold approach, utilising a dendrogram to determine a favourable split for the number of clusters and the agglomeration schedule to validate the choice (Yim and Ramdeen, 2015). We then conducted the k-means cluster analysis.

4. Results and discussion

4.1. Attribute importance and effect directions

The relative importance levels of the attributes are displayed in Fig. 1, and the results of the ANCOVA are presented in Table 3, along with the attribute importance percentages and utilities associated with the attribute levels.

The first major observation is that data governance was by far the most important attribute of the PLF-system innovation. Furthermore, the preferences expressed by the farmers clearly favoured a governance organisation consisting only of farmer representatives. As shown in Table 3, the farmers associated a clear positive utility with having the organisation led by farmers (0.87 for pig farmers and 0.72 for dairy farmers) and a clear negative utility to having the organisation led by retailers (−0.93 and −0.74, respectively), whilst perceiving the governance of the PLF-system innovation by a multi-stakeholder consortium as neutral (0.06 and 0.02, respectively). The differences between these attribute levels are statistically significant for both pig farmers ($F(2, 1702) = 164.00$, $p < .001$) and for dairy farmers ($F(2, 3787) = 247.61$, $p < .001$).

The importance ratings for the on-farm attributes were only slightly higher than those of the value-chain attributes. In both samples, farmers attached marginally more importance to the monitoring than they did to the early warning system (with the exception of dairy farmers in the Netherlands). They apparently did see the benefits of early-warning systems, however, as they preferred to have them as included part of a PLF-system innovation (0.53 for pig farmers and 0.60 for dairy farmers). This result indicates that the perceptions that farmers had with regard to PLF-system innovations were significantly influenced by whether early-warning systems had or had not been implemented (pig farmers: $F(2, 1702) = 122.34$, $p < .001$; dairy farmers: $F(2, 3787) = 41.46$, $p < .001$). In contrast, the monitoring attribute showed no significant effect. This was most likely because the monitoring of livestock is already integrated within most of the existing PLF systems available on the market, such that it is expected by default.

Although the on-farm attributes generally have a clearer direct benefit for farmers, the farmers were relatively more positive about the use of PLF to innovate at the value-chain and market-system levels. The results are nuanced, however, and they may differ slightly across countries. In the sample of pig farmers, only two of the four value-chain attributes were significant: data-sharing with control and certification organisations, ($F(2, 1702) = 11.83$, $p < .001$), and data-sharing with market innovators, ($F(2, 1702) = 12.00$, $p < .001$).

In the sample of dairy farmers, data-sharing for the purposes of monitoring and control ($F(2, 3787) = 69.84$, $p < .001$), as well as for market innovation ($F(2, 3787) = 201.73$, $p < .001$) were perceived as even slightly more important than the on-farm attributes of monitoring and early-warning systems. In addition, data-sharing with retailers had a significant positive impact in the dairy sector ($F(2, 3787) = 14.79$, $p < .001$). Dairy farmers might thus be less cautious about retailers, as co-operatives have a stronger position within the chain. This is in contrast to the pig sector, in which farmers are either highly integrated (*e.g.* through processors) within the chain or operating alone in the chain.

Interestingly, the value-chain attribute concerning data-sharing with other farmers was not significant in either of the samples. This finding suggests that farmers are reluctant to share their data with their peers, perhaps for reasons relating to competition.

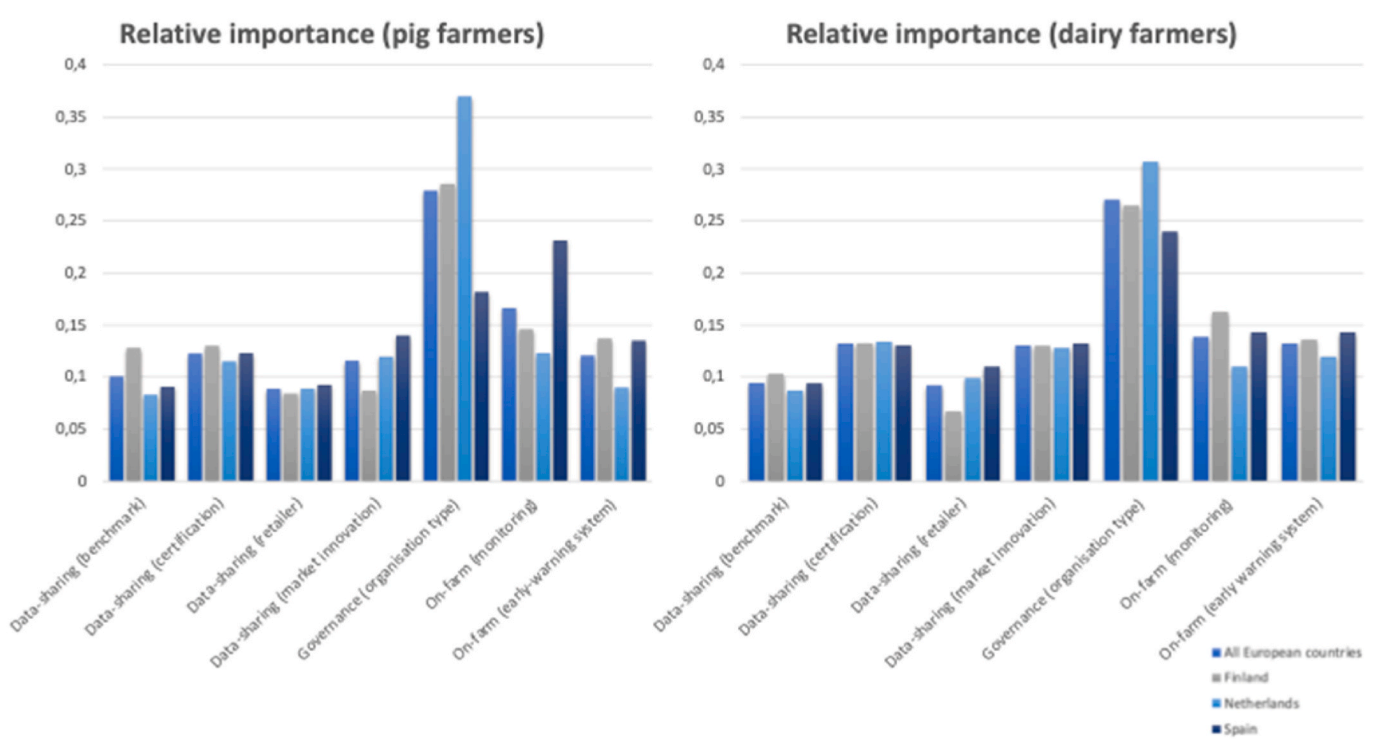

Fig. 1. Relative importance of the attributes evaluated by pig and dairy farmers.

4.2. Cluster-analysis results

Overall, the results revealed some contextual differences between countries and sectors, but no fundamental differences. This is important, as it indicates that PLF-system innovations are fundamental changes to livestock-farming systems and that farmer preferences for system attributes transcend country-specific or sector-specific differences. This does not mean, however, that the preferences of farmers are completely homogenous. To explore whether pig and dairy farmers can be grouped according to their preferences related to PLF-system innovations across countries and sectors, additional cluster analyses were conducted: one in the pig sector and one in the dairy sector.

The cluster analyses were conducted using the utility scores as indicated by the pig and dairy farmers participating in the conjoint design. We opted for hierarchical cluster analysis, given that no assumption about the expected number of clusters could be made based on literature. We therefore used the Ward's method with squared Euclidean distance to estimate the expected number of clusters for pig farmers and for dairy farmers. This was done in a two-fold approach, utilising a dendrogram to determine a favourable split for the number of clusters and using the agglomeration schedule to identify increases in coefficients to validate the choices made (Yim and Ramdeen, 2015). The dendrogram displayed an expected number of four clusters in both the pig sector and the dairy sector. These results were supported by the agglomeration schedule.

To calculate the k-means cluster analyses, the identified four clusters have been selected, using an iteration of 10. The results are displayed for pig and dairy farmers in Figs. 2 and 3 respectively, followed by the demographic characteristics of the farmers per cluster in Tables 4 and 5. Consistent across sectors, the clusters indicate a greater preference for *monitoring*, *farmer-data governance* and *market innovation*, with the largest cluster of farmers remaining *indecisive*.

The farmers in the first cluster — the 'monitoring' cluster (n = 19 in the pig sector; n = 70 in the dairy sector), assigned high utility values to the on-farm attributes of monitoring and early-warning systems, as well to data-sharing with other farmers to benchmark their performance. Pig farmers assigned to this cluster also preferred feedback loops with retailers and having retailers as the governing value-chain actors to manage, protect and distribute the PLF data collected. Dairy farmers assigned negative utility values to the sharing of data with monitoring and certification organisations, as well as to innovative businesses. They preferred to have a governance structure in which farmers have a strong vote. Farmers assigned to this cluster tended to be younger than those assigned to the other clusters, and particularly those in the 'indecisive' cluster, which included more elderly farmers. This was especially the case for dairy farmers amongst whom PLF innovation is already widespread. The 'monitoring' cluster also exhibited a higher level of technology adoption than the other clusters did (Morris and Venkatesh, 2000).

Pig and dairy farmers assigned to the second cluster — the 'farmer data governance' cluster (n = 54 in the pig sector; n = 14 in the dairy sector) — attached by far the greatest importance to the attribute concerning the governance structure of the organisation that manages, collects and distributes PLF data. Moreover, they expressed negative preferences for other types of governances (*e.g.* a system governed by retailers or multi-stakeholder consortia, including farmers). Pig farmers assigned to this cluster indicated that they would like to share data with companies to drive innovation but associated low benefits with the attribute of cooperating with retailers. Similar results were found for dairy farmers, with the difference that dairy farmers expressed a desire to take more influence and responsibility for the PLF-system innovation. Notably, more than 71% of all pig and dairy farmers in the 'governance' cluster expressed a willingness to invest in PLF if they could expect to manage the PLF-system innovation themselves. Furthermore, in the pig sector, the 'governance' cluster comprised a significant number of farmers with large animal populations.

Pig farmers assigned to the third cluster — the 'market innovative' cluster (n = 56 in the pig sector; n = 51 in the dairy sector) — preferred a

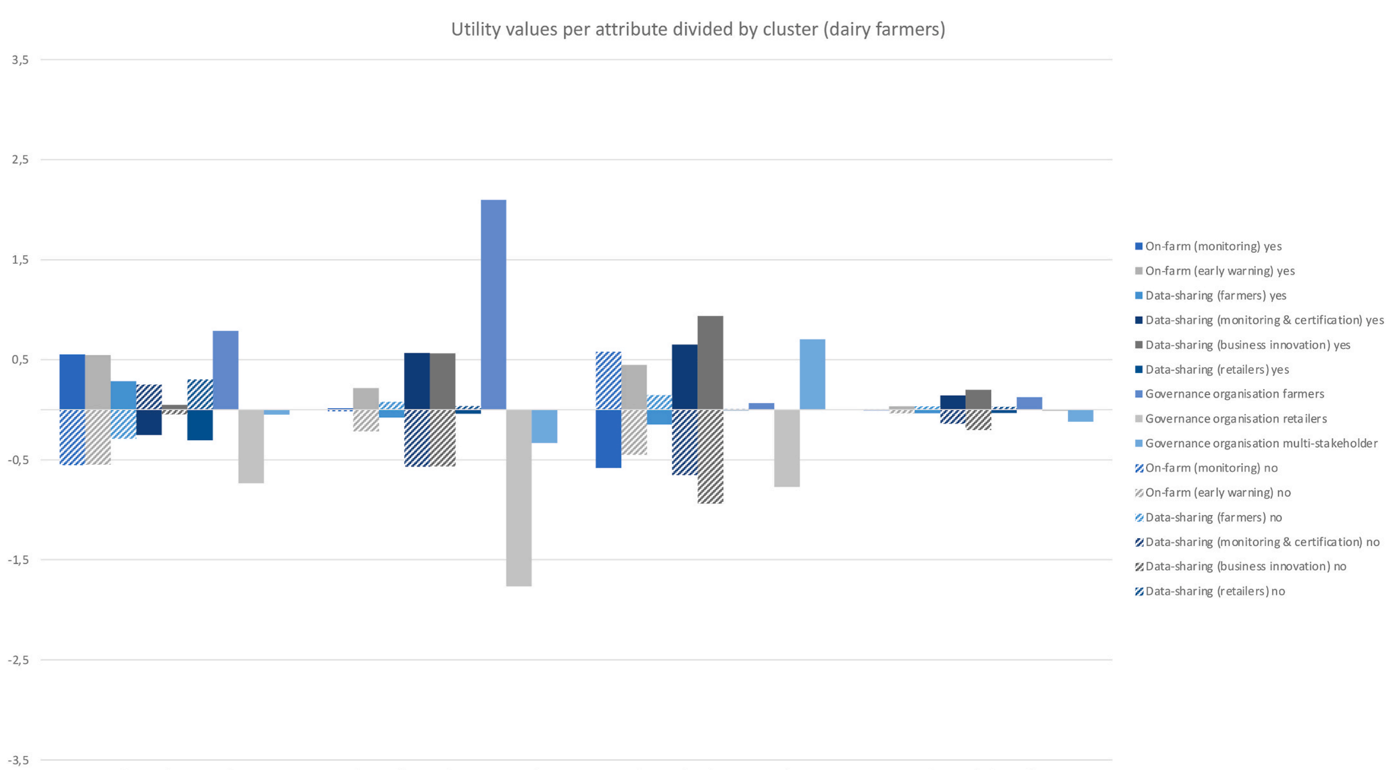

Fig. 2. Utility estimates per attribute for the four clusters of dairy farmers. Higher utility scores display a greater likelihood for the attribute level displayed. For two-level attributes, the utility score is mirrored (marked in striped bar) while for multilevel attribute levels, different utility scores exist.

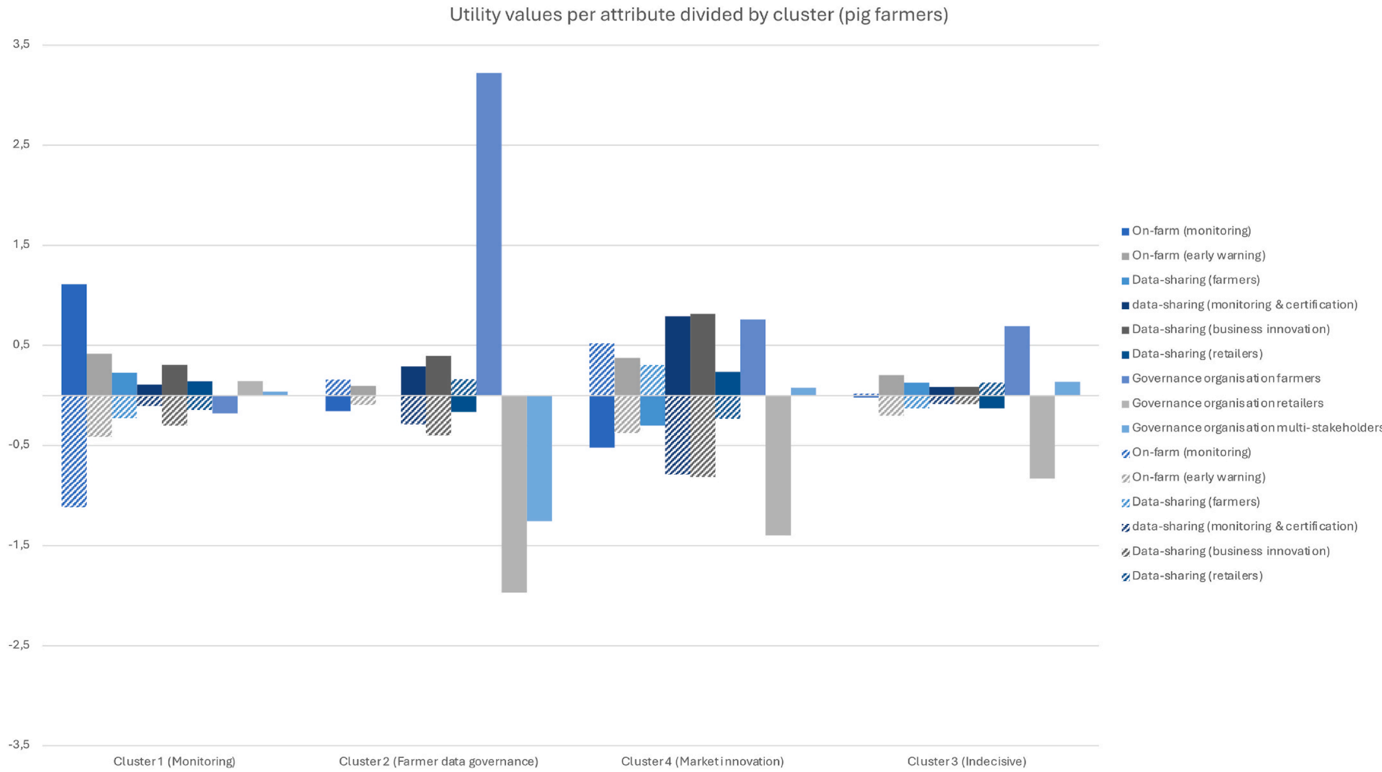

Fig. 3. Utility estimates per attribute for the four clusters of pig farmers. Higher utility scores display a greater likelihood for the attribute level displayed. For two-level attributes, the utility score is mirrored (marked in striped bar) while for multilevel attribute levels, different utility scores exist.

system governed solely by farmers, while dairy farmers preferred a multi-stakeholder approach to governance. This difference could be traced back to fundamental differences between farmers in the two sectors with regard to their relationship-building with other value-chain actors, which subsequently influence the level of operations and cooperation (Schulze et al., 2006). One example of this is the integration of the value chain of Spanish pig farmers. In Spain, the processing of speciality products (*e.g.* ham and sausage) is traditional and well-established. In contrast, other countries are more likely to be characterised by mainstream production, which is associated with greater dependence on large-scale processing and retail. Moreover, farmers in the ‘market innovation’ cluster attached high preferences to sharing information with monitoring and control organisations, innovative businesses and retailers. The ability of farmers to innovate within their product portfolios based on the way in which they produce animal-based products thus remains an important attribute in PLF-system innovation for farmers. The farmers in this cluster also had farms of medium size, as estimated by the number of animals. Although farmers apparently do see some merits in the use of technology, some are still indecisive concerning the potential utility of PLF for themselves. This issue was observed particularly amongst pig farmers.

Compared to the previously mentioned clusters, the utilities that pig and dairy farmers assigned to the fourth cluster — the ‘indecisive’ cluster (n = 25 in the pig sector; n = 78 in the dairy sector) — revolved around zero, thus indicating that farmers were relatively indecisive about their preferences related to PLF-system innovations and their attributed values. Interestingly, the largest proportion of farmers in each sector (49% of pig farmers and 31% of dairy farmers) could be assigned to the ‘indecisive’ cluster. As indicated by this important aspect, the majority of pig and dairy farmers in this cluster did not perceive any added benefits to contributing to/using PLF-system innovations.

5. Implications

This article adopted a design-oriented approach to exploring PLF-system innovations. Whereas earlier studies on PLF have acknowledged that the implications of PLF extend beyond the farm level, there has been a notable lack of studies on the design of PLF-system innovations. In this article, we identify dimensions of PLF-system innovations pertaining to on-farm, data-sharing in the value chain (with retailers, certifiers and control organisations, other farmers, and market innovators), and data governance. We focus on farmers — the primary producers of PLF data — by investigating their preferences and perceptions based on a conjoint study conducted across three European countries. The main findings indicate that farmers generally exhibit a favourable attitude towards PLF-system innovations, albeit under certain conditions. More specifically, they are supportive of such innovations when their data are governed by farmer organisations, when the innovation encompasses on-farm attributes (*e.g.* early-warning mechanisms), and when the data can be shared with oversight and regulatory bodies, whilst also being harnessed for market-oriented innovations. These findings carry significant implications that can guide the practical development of PLF-system innovations in livestock farming. We discuss these implications below in the following order: data governance, on-farm applications, PLF-system innovations within the value chain, and sectoral differences.

5.1. Data governance

The governance of data-sharing and management is undoubtedly crucial to securing farmer participation in the evolution of PLF-system innovations. In addition to being in place, such governance should rest primarily within the hands of farmers themselves or their designated representatives. Although farmers logically place the most trust in their own representatives (Zhang et al., 2017), the difference with other structures (even multi-stakeholder platforms) is considerable. Although

Table 4
Demographic cluster information on dairy farmers.

Dairy farmer clusters	1	2	3	4
Name	**Monitoring**	**Governance**	**Market innovative**	**Indecisive**
n =	70	54	51	78
Netherlands	49 (%)	41 (%)	36 (%)	57 (%)
Finland	12 (%)	9 (%)	4 (%)	4 (%)
Spain	9 (%)	4 (%)	11 (%)	17 (%)
Mean age				
Mean age	47.1	45.7	48.1	50.3
Number of animals				
Number of animals >500	7 (%)	3 (%)	1 (%)	3 (%)
Number of animals 201-500	9 (%)	3 (%)	10 (%)	12 (%)
Number of animals 101-200	24 (%)	29 (%)	17 (%)	29 (%)
Number of animals 50-100	27 (%)	16 (%)	16 (%)	28 (%)
Number of animals <50	2 (%)	3 (%)	7 (%)	5 (%)
Technology integration				
Technology integration is useful: Yes	22 (%)	23 (43%)	25 (49%)	21 (27%)
Technology integration is useful: Most likely yes	37 (%)	24 (44%)	18 (35%)	40 (51%)
Technology integration is useful: Indecisive	11 (%)	6 (22%)	7 (14%)	15 (19%)
Technology integration is useful: Most likely not	0 (0%)	2 (2%)	1 (2%)	2 (3%)
Technology integration is useful: Not	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Willingness to investment				
Willingness to invest in PLF in the near future: Yes	42 (60%)	38 (70%)	28 (55%)	41 (53%)
Willingness to invest in PLF in the near future: Indecisive	16 (23%)	10 (19%)	12 (24%)	21 (27%)
Willingness to invest in PLF in the near future: No	5 (7%)	2 (4%)	1 (2%)	4 (5%)
Quitting within the next 10 years				
Yes, I will stop, but I have a successor	9 (20%)	4 (10%)	6 (12%)	10 (13%)
Yes, I will stop, and the farm will be closed	5 (11%)	1 (3%)	2 (4%)	7 (9%)
No	20 (44%)	27 (50%)	21 (41%)	27 (35%)
I do not know	11 (24%)	6 (11%)	5 (10%)	12 (15%)
Missing values	25 (17%)	16 (9%)	17 (9%)	22 (17%)

Table 5
Demographic cluster information on pig farmers.

Pig farmer clusters	1	2	3	4
Name	**Monitoring**	**Governance**	**Market innovative**	**Indecisive**
n =	19	14	56	25
Netherlands	4 (21%)	13 (93%)	45 (80%)	15 (60%)
Finland	4 (21%)	0 (0%)	6 (11%)	3 (12%)
Spain	11 (58%)	1 (7%)	5 (9%)	7 (28%)
Mean age				
Mean age	42.5	47.2	49.4	44.6
Number of animals				
Number of animals >500	5 (26%)	7 (50%)	10 (18%)	10 (40%)
Number of animals 201-500	6 (32%)	5 (36%)	22 (39%)	10 (40%)
Number of animals 101-200	4 (21%)	1 (7%)	12 (21%)	5 (20%)
Number of animals 50-100	2 (11%)	1 (7%)	8 (14%)	0 (0%)
Number of animals <50	2 (11%)	0 (0%)	2 (4%)	0 (0%)
Technology integration				
Technology integration is useful: Yes	12 (63%)	4 (29%)	12 (21%)	11 (44%)
Technology integration is useful: Most likely yes	4 (21%)	6 (43%)	32 (57%)	8 (32%)
Technology integration is useful: Indecisive	3 (16%)	3 (21%)	9 (16%)	4 (16%)
Technology integration is useful: Most likely not	0 (0%)	1 (7%)	3 (5%)	2 (8%)
Technology integration is useful: Not	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Willingness to investment				
Willingness to invest in PLF in the near future: Yes	7 (37%)	10 (71%)	26 (46%)	10 (40%)
Willingness to invest in PLF in the near future: Indecisive	4 (21%)	2 (14%)	17 (30%)	8 (32%)
Willingness to invest in PLF in the near future: No	2 (11%)	1 (7%)	4 (7%)	2 (8%)
Quitting within the next 10 years				
Yes, I will stop, but I have a successor	0 (0%)	0 (0%)	4 (7%)	1 (4%)
Yes, I will stop, and the farm will be closed	2 (10%	1 (7%)	3 (5%)	0 (0%)
No	0 (0%)	7 (50%)	24 (43%)	9 (36%)
I do not know yet	1 (5%)	5 (36%)	8 (14%)	4 (16%)
Missing values	16 (85%)	1 (7%)	17 (30%)	11 (44%)

the results are compelling in this regard, they do raise questions concerning the role that farmer organisations should play in the digital transformation of the livestock industry in order to reassure farmers that PLF-system innovations simultaneously promote the awareness, security, credibility and legitimacy of the information they produce and use within them (Cash et al., 2003). Within the context of the digital agricultural transition, therefore, farmer organisations may play two different roles. They may act as the *orchestrators* of system innovations, thus taking everything in their own hands, or they may act as *watchdogs* at a safe distance, leaving the innovation to others, but safeguarding them in their own interest and applying the brakes when the interests of their members are violated. If farmer organisations have the ambition to become the orchestrators of PLF-system innovations, they should logically also be equipped with certain levels of *(1) proactiveness* (Ingenbleek and Krampe, 2023), meaning that they can take the lead in taking the next steps in accomplishing the system innovations through digital technologies (Marvin et al., 2022); (2) *market visioning* (cf. Tellis, 2006), meaning that they can portray how they market and how the system could be transformed through a given PLF-system innovation; (3) acting as a *linchpin*, connecting and engaging all other stakeholders who play a role in the system; and (4) *agility*, in that they can change plans when things do not work out as planned or when technological, social, economic or other circumstances change along the way.

Whether as '*orchestrators*' or '*watchdogs*', farmer organisations taking up either of these roles should have access to the data infrastructure, and they should possess the technological data-management abilities that they need to oversee what happens with the farmers' data. It can thus not be assumed that all farmer organisations can play (or that farmers want them to play) a role in PLF-system innovations. There may be a need for capacity-building, which may subsequently benefit from policy support that sets the boundaries in which the organisation can operate (*e.g.* Ashley and Maxwell, 2001; Kaur et al., 2022).

5.2. On-farm applications of PLF

Although the results of our study indicate that farmers are open to PLF-system innovations, they do prefer systems to be equipped with on-farm attributes. In other words: farmers will be more likely to adopt PLF-system innovations that could transform systems towards greater efficiency, sustainability, animal welfare or other goals with common interests if the same systems also include state-of-the-art (PLF) attributes that support farming operations. According to our results, these attributes particularly include data-driven early-warning systems. If such attributes are offered as part of a broader PLF system innovation, instead of in the form of separate services, farmers may perceive them as more convenient (examples could include updates that come with the subscription to the larger package). Notably, the costs involved could also play a role. Although on-farm benefits obviously cost money, value-chain attributes could allow farmers to gain money as well, thus making it relatively less expensive to have all of the latest technological features at no additional costs (and without having to worry that their data will end up in the wrong hands, as they are governed by their own representatives).

5.3. PLF-system innovations through data-sharing within the value chain

The results also show that the system attributes at the level of the value chain (and particularly data-sharing for purposes of monitoring and control, as well as for market-innovation) are perceived positively by farmers. In a sense, the results on monitoring and control reflect could be regarded as '*low-hanging fruit*': the sharing of PLF data could allow monitoring and control organisations to do their jobs with fewer or none of the more labour-intensive farm visits, in addition to enabling farmers and certification organisations to establish relationships of trust from the outset, thereby eliminating the need for lengthy processes aimed at building trust and commitment (Sahay, 2003).

The result that farmers also have positive perceptions of market innovation is perhaps more surprising, as this attribute is accompanied by uncertainty concerning whether the expected innovations will actually be performed and whether it will indeed lead to higher revenues for farmers (and/or perhaps other stakeholders). The key idea is that PLF-system innovations could disrupt the current state of affairs, in which farmers might feel trapped in a system that limits their decision-making freedom, as a powerful chain member determines the standards with which farmers must comply. In this respect, PLF-system innovations may give them hope for greater decision authority (cf. Pauschinger and Klauser, 2022). To date, farmers wishing to differentiate their production from the mainstream have only a few options. First, they could take on a label or certificate (*e.g.* organic certification) by adopting farm practices that meet specific requirements. Given that many farmers make use of such labelling schemes, however, the labels will not make them unique (Ingenbleek and Krampe, 2022). The 'market innovation' attribute of PLF-system innovations could help farmers to take on different breeds of farm animals or to advertise their products as locally produced. Without a PLF system, such claims are very difficult for buyers to verify. Along with the data they generate, PLF-system innovations can offer highly precise information on animal welfare, environmental impact, origin and similar factors, thus allowing differentiation between farms, farming systems, and places of origin, as well as between individual animals. Such innovations could make hard data available, for example, to prove that animals had a significantly better life than the average farm animal in a given sector or even on a farm, thus possibly leading to overall improvements in animal welfare improvements due to fierce competition. Farmers who are able to find buyers who are willing to pay more for such animals would also have an incentive to provide proof that more of their animals have had a demonstrably better life. The connection between animal welfare and financial rewards would thus become very direct, as evidenced by PLF data. The better life that farmers establish depends not only on characteristics of husbandry systems. Farmers could also experiment with their own ways of improving the lives of their animals, thus gaining further control over their farm decisions. Differences obviously exist between sectors. For dairy farmers it might be much more difficult to differentiate between animal heads than it is for pig or other meat farmers. With decentralised milk-processing plants, however, it could also become more feasible to distinguish milk from different animals (Lely, 2024).

5.4. Sector differences

Differences exist between farming segments (*e.g.* between pig and dairy farmers). These differences are driven by the career stages of farmers, the market environments in which they operate and their individual perceptions of and willingness to contribute to PLF-system innovation. In general, however, farmers perceive PLF-system innovations to be of assistance in their daily work, resulting in an increased perceived of usefulness and a greater willingness to invest in PLF solutions. Depending on the market environment, however, some attributes are likely to become more important than others. For example, Spanish pig farmers, who operate within a highly integrated market and who thus tend to have strong ties to processors (Granovetter, 1983), are more willing to invest in PLF technologies that support their current livestock systems, and they tend to see value primarily in the on-farm attributes of PLF systems (*e.g.* early warning systems). Dutch and Finnish farmers are apparently willing to invest in PLF-system innovations that have strong value-chain features, as long as they have a strong voice in the governance of PLF-innovation systems. In summary, the results of our study suggest that PLF-system innovations are most effective when they consider the current or future needs of farmers by requiring them to be designed according to such intrapersonal and market needs.

6. Limitations and future research directions

The findings from this study should be interpreted in the light of its limitations. First, collecting data from farmers is becoming increasingly difficult. We therefore had to settle for convenience samples in the three European countries. The response rates were different in the three European countries, resulting in different sample sizes. In this respect, the results should be interpreted with caution, as they are not equally representative of farmers from the three European countries involved.

Second, although the method of conjoint analysis has important features for comparing different attributes of a PLF-system innovation, it is also limited in the number of attributes that it can include. Although we incorporated attributes to test the holistic idea of and farmer preferences for PLF-system innovations, we did not incorporate other attributes (*e.g.* data-sharing with policymakers for the purposes of designing new sector-level policies; data-sharing with animal-feed providers, veterinarians or pharmaceutical companies). These actors can be part of PLF-system innovations as well. Future research could further identify the preferences of farmers for these and, possibly, other attributes. In addition, given the orthogonal design of the conjoint study, we were able to investigate only the main effects and no interaction effects between attributes. Future research might therefore also take these interactions into account.

A third limitation of our study is that many other questions must be answered before PLF-system innovations can actually be launched. For example, PLF-system innovations have many potential '*customers*' who could benefit from the services that are created based on PLF data. Although we examine the role of farmers in this study, research remains limited with regard to consumer acceptance or rejection of offerings produced under the umbrella of PLF-system innovations. To be of a transformative nature, PLF innovations must be extended to consumers, as consumer markets are one of the engines of transformative change in the food system. To date, most research on consumer preferences regarding PLF has been in the form of qualitative studies (*e.g.* Krampe et al., 2021). Future research should thus extend such work with quantitative studies identifying the preferences and importance ratings of consumers, as well as different market segments. Such information could help to assess the viability and most desirable form of PLF-system innovations from another group of heterogeneous independent decision-makers who collectively have a profound influence on the development of the sector. In this way, quantitative consumer studies could provide important complementary insights to the perspectives of farmers and the perspective of value-chain actors operating in the '*hidden middle*' of livestock value chains.

A fourth, and final limitation of our study is that complex systems (*e.g.* PLF system innovations) are unlikely to be introduced in their final form. Ongoing, iterative implementation processes are of vital importance to any food-system transition, to ensure that the needs of actors can be met effectively. As such, PLF-system innovations are likely to be introduced in relatively simple forms with fewer attributes that serve only a few actors and their needs, whilst anticipating subsequent steps in which they grow to be of relevance to other actors with new attributes. In addition, PLF and the underlying innovative technologies have several limitations that need to be overcome to make PLF systems a sustainable part of the dairy and pig sectors. These integrate technology-related questions, such as those related to data ownership, the role of private networks in cloud computing solutions and the digital infrastructure as a whole, but also macro-level factors, such as the governance and management of data or the transfer of data via national or international networks, which need to be considered in future research. According to Wolfert et al. (2017), future developments will determine whether we work towards an open, collaborative system involving farmers and all stakeholders in the chain network, or a closed, proprietary system in which the farmer is part of a highly integrated food supply chain. Despite our positivistic approach outlined in this study, it should, therefore, be obvious that the mentioned challenges need to be solved first. Future studies should therefore analyse the adoption and growth scenarios of PLF system innovations, taking the farmers' perceptions into account. Although this will probably require the integration of stakeholder opinions, it should go beyond taking inventory of the demands and wishes of stakeholders to address the actual implementation steps needed to scale the system. Once basic growth strategies have been determined in this manner, the path would be clear for concrete technological and financial feasibility studies aimed at developing the system in a more concrete manner that could lead towards commercialisation.

A fifth and final observation is that while we have identified farmers as causal actors beyond European borders, we have not dived deeper into market and governance-driven differentiations that affect farmers. This therefore remains an important topic for further research, to explore the leverage points that can drive sustainability transformation from the farmers' perspective.

7. Conclusion

In the design of farmer-centric PLF-system innovations to foster acceptance by farmers, one priority must be to create an organisational structure that governs the system and in which farmers have a strong voice. The system attributes preferred by farmers in a highly integrated market environment (on-farm attributes) are different from those preferred in innovative market environments (the ability to share data to optimise procedures for control and certification and/or to define new market opportunities). The widespread adoption of PLF-system innovations and data-sharing requires concrete proof of the personal, system and sector-dependent benefits associated with the value system that reach above and beyond European borders.

Appendix 1: List of experts participating in the interviews

	Sector	Position/background	Country
	Farmers and producers		
1	Pig farming	Veterinarian	Spain
	Pig farming	Responsible for project management	Spain
2	Pig farming	Veterinarian	Spain
3	Pig farming	Veterinarian	Spain
4	Pig farming	Head of production and environment	Spain
5	Pig farming	Head of production and environment	Netherlands
6	Dairy farming	Quality manager	Spain
	Dairy farming	Responsible for new developments	Spain
7	Fairy farming	Technical analyst for dairy cattle	Spain
8	Fairy farming	Expert in cow nutrition	Spain
	Pig and dairy farming	Veterinarian	Spain
9	Dairy production	Quality manager	Italy
10	Dairy production	Veterinarian	Finland
11	Dairy production	Dairy administration person	Finland
12	Dairy farming	CEO	Finland
13	Dairy farming	CEO	Finland
	Farmer cooperatives		
14	Dairy framing organisation	Research & development manager	Netherlands
15	Farming organisation	Animal production specialist	Finland
16	Farming organisation	Director and expert in pig farming	Finland
17	Animal feeding	CEO	Netherlands
18	Animal feeding	Director	Spain
	Slaughterhouses and processors		
19	Meat processing and slaughtering	Research & development manager	Netherlands
	Meat processing and slaughtering	Research & development manager	Netherlands
20	Meat processing and slaughtering	Veterinarian	Spain
	Retailing, certification and labelling		
21	Labelling, certification and packaging	Public relationship manager	Netherlands
22	Retailer	Corporate responsibility technician	Spain
23	Labelling, certification and packaging	Head of animal welfare certification	Spain
	Technology providers		
24	Technology provider	Animal welfare manager	Spain
	Technology provider	PLF manager	Spain
25	Technology provider	Veterinarian specialising in animal nutrition	Spain
26	Technology provider	Consultant and commercial party	Spain
27	Technology provider	Manager	Finland
	Consultants and researchers		
28	Consultancy (meat production)	CEO	Netherlands
29	Consultancy (meat production)	Specialist in animal welfare	Netherlands
30	Research and academia	Professor and CEO	Netherlands
31	Research and academia	Senior researcher	Netherlands
32	Research and academia	PLF expert	Netherlands
33	Research and academia	Expert in animal-sensor research	Spain
34	Research and academia	Expert in sensors for cheese transformation	Spain

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	Sector	Position/background	Country
35	Research and academia	Veterinary expert in cow reproduction	Spain
36	Research and academia	PLF expert	Sweden
37	Research and academia	PLF expert	Sweden
38	Research and academia	PLF expert	Sweden
	Animal interest groups		
39	Animal interest group	CEO	Netherlands
40	Animal interest group	Policy officer	Netherlands
41	Animal interest group	Responsible for animal welfare	Spain
42	Animal interest group	Expert in animals used for production	Spain
43	Animal interest group	Director	Finland
	Public administration		
44	Public administration	Senior officer	Finland
45	Public administration	Expert in strategic food planning	Spain

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CRediT authorship contribution statement

Caspar Krampe: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Paul T.M. Ingenbleek:** Writing – review & editing, Conceptualization. **Jarkko K. Niemi:** Writing – review & editing, Conceptualization. **Jordi Serratosa:** Conceptualization.

Data availability

Data will be made available on request.

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