



Deliverable D3.2

Case studies follow-up report

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Abstract:	The Digi4Live project aims to enhance the capacity of the livestock sector actors across Europe to harness data-generating and digital technologies effectively. The project uses a multi-actor co-creation approach that engages stakeholders across the livestock value chain, from farm to fork, including technology suppliers, competent authorities, intermediates, retailers and research and development initiatives. To reach the goal of developing innovative digitalised data and technology solutions the project has six case studies that aim to develop digitalization concepts which have the potential for EU-wide upscaling. The case studies investigate the following topics in digitalization (A) the generation of new datasets in animal health and welfare, (B) enhancing value chain resilience and transparency, (C) developing robust artificial intelligence (AI) methods for sensor-based animal tracking, (D) integrating different technologies and data, including animal breeding, (E) making use of data digitalization for environmental impacts assessment, and (F) investigating digital solutions in policy and impact monitoring and public administration. This deliverable summarizes the six case studies indicating the aims and scopes, the results from during the first 18 months of the project, current conclusions and plans for the implementation during the following 18 months. The deliverable includes results from reviews, collected datasets, software tools, data space concepts and AI models. The work of the case studies will continue for another 18 months and the economic and environmental impacts of the developed concepts will be assessed. Each of the case studies has proceeded according to the plan and will expand the activities during the next 18 months. The case studies actively seek collaboration with new stakeholders and their results and progress are widely disseminated through public webinars and through attendance in large scientific and industry and farmer events.

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Table 1. List of abbreviations and acronyms

List of Abbreviations and Acronyms	
AI	Artificial intelligence
API	Application programming interface
CS	Case study
DPP	Digital Product Passport
EBV	Estimated breeding value
EU	European Union
EU-PEF	EU Product Environmental Footprint
KPI	Key performance indicator
LCA	Life cycle assessment
TRACES	Trade Control and Expert System
WP	Work package

1. Introduction

Digi4Live aims to **enhance the capacity** of the livestock sector actors across Europe to harness data-generating and digital technologies effectively. The project uses a multi-actor (co-creation) approach (Franco Ferreira et al., 2019) that engages stakeholders across the livestock value chain, from farm to fork, including technology suppliers, competent authorities, intermediates, retailers and research and development initiatives. Through co-creation of digital and data solutions, Digi4Live fosters greater adoption of technologies and data for livestock tracking and tracing.

To reach the goal of developing innovative digitalised data and technology solutions the project has six case studies (Figure 1) that aim to develop digitalization concepts which have EU potential for EU-wide upscaling. The case studies have been planned so that they cover a broad set of technologies and are applied to several livestock species: dairy and beef cattle, pigs and poultry. The case studies investigate the following topics in digitalization (A) the generation of new datasets in animal health and welfare, (B) enhancing value chain resilience and transparency, (C) developing robust artificial intelligence (AI) methods for sensor-based animal tracking, (D) integrating different technologies and data, including animal breeding, (E) making use of data digitalization for environmental impacts assessment, and (F) investigating digital solutions in policy and impact monitoring and public administration.

The case studies will be completed in the first 36 months of the project and economic and environmental analysis of the case study outcomes are performed in the following 18 months. The implementation plan for the case studies was developed during the first year of Digi4Live with a broad group of stakeholders using the design thinking approach. The progress has been presented regularly in public webinars and at relevant conferences and fairs.

This deliverable is a mid-term report of the progress of case studies. We introduce the aims of the case studies, presents the results from the first 18 months of work, present a plan for the continuation of each case study and present our first conclusions.

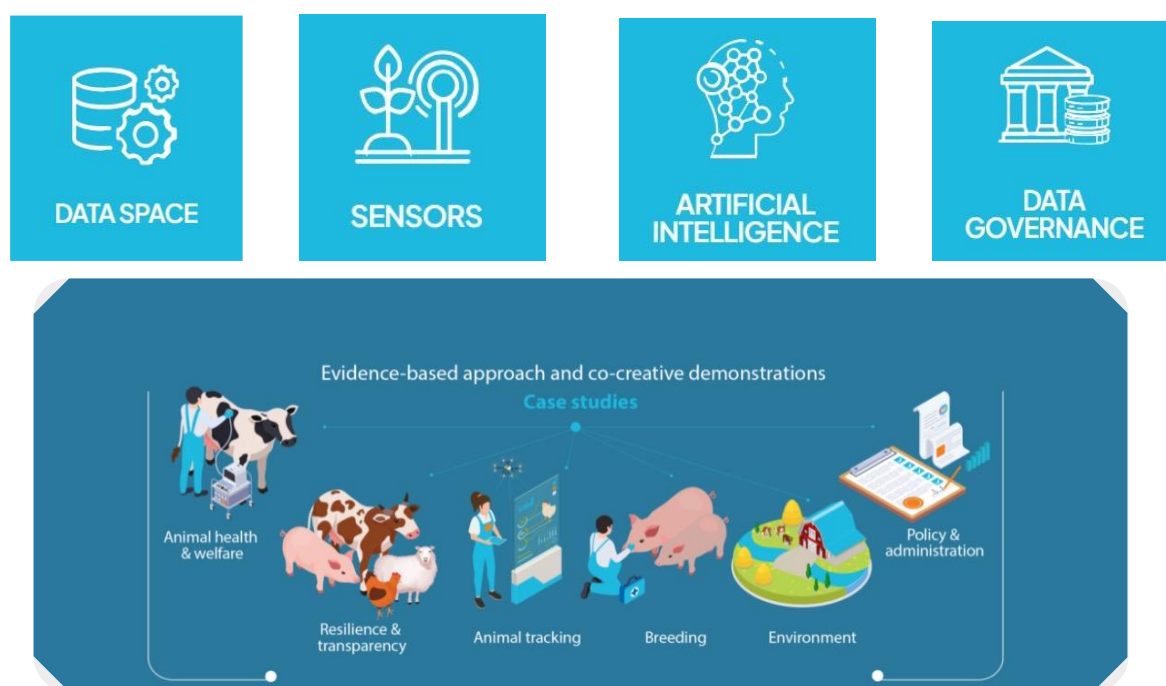


Figure 1. Digi4Live case study application areas and key cross-cutting digital technologies.

2. Methodology for the case studies

2.1 Designing the case studies

The case studies in the Digi4Live project utilise a **design thinking approach**. Design thinking is a non-linear, iterative process that aims to understand stakeholders, challenge assumptions, redefine problems and develop innovative technology and data-driven solutions that are then prototyped and tested (Tschimmel, 2012). To address ill-defined or unknown problems within the six case studies, a five-phase approach is used, comprising the i) empathise, ii) define, iii) ideate, iv) prototype and v) test/evaluate phases. The earlier steps of developing the case studies have been described in deliverable D3.1.

2.2 Economic and environmental data collection

Besides the steps of the technical design, and to reflect on the data needs for Work Package 7 (WP7), Digi4Live's case studies will follow a predefined data collection strategy that will enable developing an integrative economic and environmental analysis. It is recognized that WP7 will examine digital and data-driven solutions for livestock tracking and tracing solutions. Hence, the focus will be on the impacts of digital and data-oriented technologies and how they contribute to possible empirical applications and processes.

For the economic analysis, the following steps are foreseen:

- (1) Collecting data for the baseline situation (non-digital or unimproved solution) and the improvement strategy (digital solution).
- (2) Identifying case study-specific sources of costs and benefits, and building a database, including price information related to technical and other parameters or cost items (see e.g. Chibanda et al. 2020; Thobe et al., 2020), for the upcoming analyses.
- (3) Performing qualitative analysis that assesses:
 - *Economic and societal barriers and gaps* for adopting data-oriented and digital solutions, including their affordability and feasibility.
 - *Value chain structures* to evaluate the value-adding potential of innovative digital strategies along the value chain.
 - *Readiness potential* of the current market to accept new technology-based applications.

For the environmental impact analysis, data from case studies will be collected following a Life Cycle Assessment (LCA) approach (c.f., van Zanten et al., 2018). This approach requires defining the following items for each case study (c.f., European Commission, 2018):

- (1) The goal of the assessment (e.g., investigation of the effects of digital solutions on the environmental performance of the system).
- (2) The scope of the assessment (e.g., system boundaries (foreground and background systems: the processes of the supply chain system that will be included in the analysis), main functions and functional unit(s), time boundaries (the period considered relevant for the analysis will be in the focus of data collection), life cycle impact assessment method and environmental impact categories and relevant indicators).
- (3) The primary data input needs to complete existing gaps within the data structure.

As primary data will be used to complete existing secondary data gaps, developing primary data collection protocols for each case study is also required. Therefore, the following general steps will be used (e.g. European Commission, 2018; Fazio et al., 2020):

- (1) Collecting the primary data for baseline systems and 'digital solution' systems of case studies.
- (2) Developing the LCA datasets for the foreground systems (the processes of the supply chain for which primary data will be collected and are important for the environmental performance of the system)

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for both the baseline system and the 'digital solution' system of case studies, using an LCA software (e.g., SimaPro).

- (3) Completing the LCA models for both the baseline system and the 'digital solution' system of case studies, involving relevant data from international secondary datasets (for the background system), using an LCA software (e.g., SimaPro).
- (4) Estimating the effects of the digital solution on the different environmental impact category indicators and the total environmental score of the system defined for case studies.

3. Case study progress reports

In the subsequent section, six case studies are outlined, indicating the aims and scopes, the results from during the first 18 months of the project, current conclusions and plans for the implementation during the following 18 months.

3.1 Case study A: Generation of new data sets on animal health and welfare

Aims and background

Case Study A focuses on developing harmonised datasets for pig and broiler production chains, integrating livestock health and welfare data to increase welfare and health levels in the production chain. The case study will demonstrate how to make datasets digital and how to connect them with other data to generate a single data resource in broilers and pigs. For this purpose, a concept of digitally operated animal welfare assessment framework addressing the multidimensionality of animal welfare will be first established as a desk study, then co-developed with stakeholders and finally validated. The expected outcome of the case study is a data-driven Welfare Quality framework that shows the potential of connecting and harmonising animal welfare and health data, including sensor-based data and market-based solutions.

The case study elaborates two specific cases, one for the broiler production chain and another for the pig production chain. The activities include integrating livestock health and welfare data into a centralised database to improve insight into welfare and health levels achieved in the broiler and pig production chain and assist targeted management to improve these levels; accessing the environmental impacts of data integration through Environmental Life Cycle Assessment; establishing data-driven solutions for benchmarking, improving production transparency, and enabling better decision-making across the value chain and its actors. The outcomes of CS-A have the potential to benefit stakeholders. For example, competent authorities can monitor farm animal welfare and health status, identify risks, and help the industry to develop best practices, benchmarking tools, and transparent product quality solutions. Data integration is required to monitor animal welfare and health to meet regulatory or labelling requirements; or simply to improve product quality or profit margin. Retailers and consumers require guaranteed welfare and health levels in the production chain. Farmers' insights into animal welfare and management practices must be taken into account, as these can enable more targeted animal care, leading to improved performance and a reduced need for medication.

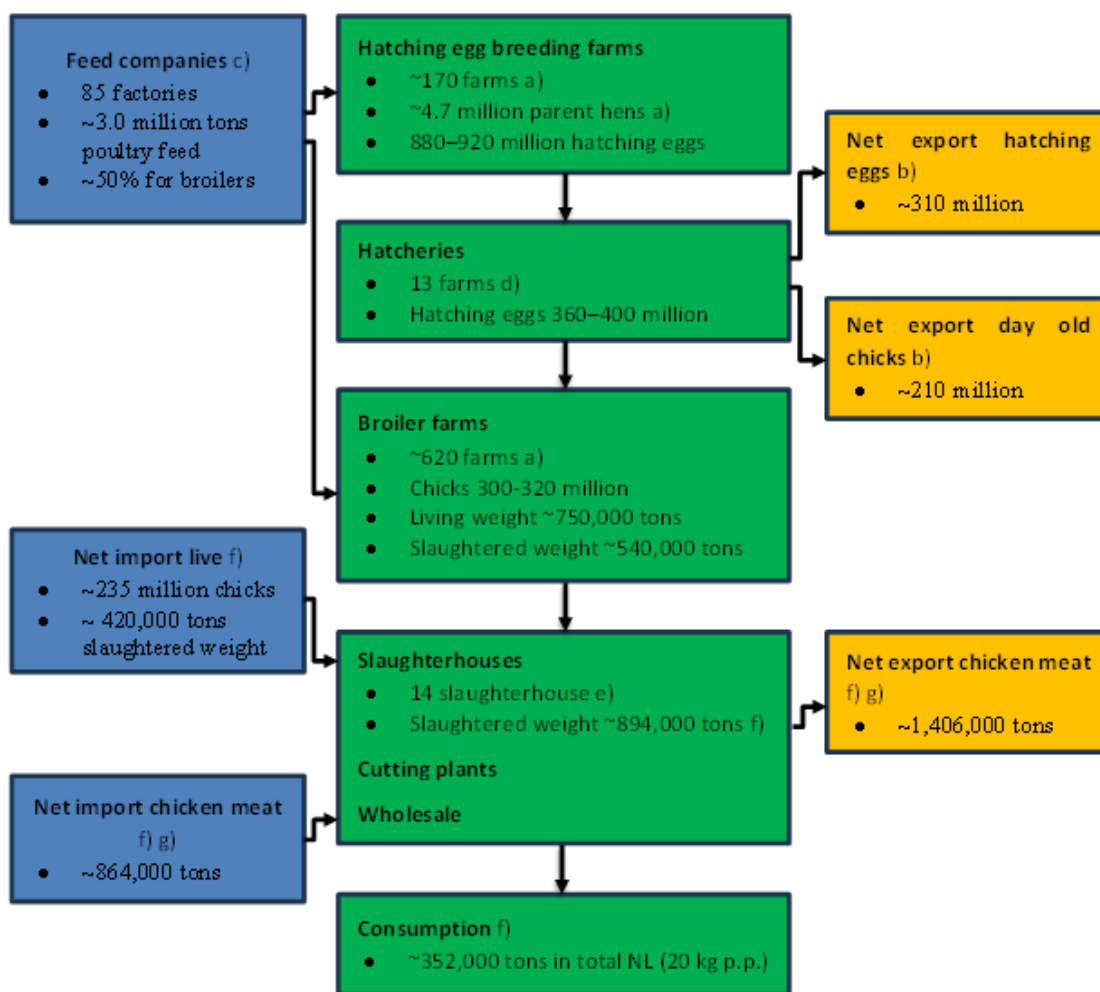
This case study contributes to the Digi4Live project's objective of enhancing data sharing in livestock value chains. It builds upon EU sustainability policies, aligning with the Product Environmental Footprint (PEF) methodology, to improve welfare and health in the pig and broiler production chain and to link animal welfare and health metrics at different production stages with environmental and economic impacts. By generating new datasets, the case study addresses critical challenges such as data harmonisation and visualisation, benchmarking, management support, stakeholder collaboration, acceptance of AI tools by stakeholders and environmental impact assessments.

Multiple actors along the value chain are relevant for this case study. In the first stages of case study development, CS-A will utilise data from the Netherlands. Figure 2 shows how the Dutch broiler chain is organised and what is the number of animals, farms and chain companies involved. Although the case study will primarily focus on farms, slaughter plants, hatcheries and veterinary services, it will also connect to other actors of the business ecosystem. Figure 3 shows how the Dutch pig chain is organised, what animal numbers are involved as well as the number of farms and companies that are involved. The pig case study will primarily focus on farm and slaughter plants. In addition, the opportunities for using the concepts resulting from the case study across public and other private stakeholders will be explored. In terms of operationalisation, the broiler case study will be more advanced than the pig case study.

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Specific aim and approach of case study A for broiler chickens is the application of AI on standard farm data of water consumption patterns to predict flock welfare and health. The water flow can quite easily be monitored on flock level with water flow sensors. The water consumption of broilers is closely related to feed intake, the stable climate and the well-being of the animals. Next to the water also other available parameters, such as air pressure, CO₂, external temperature, feed running, humidity, internal temperature, lighting, outside humidity, outside relative humidity, outside temperature, outside wind speed, pressure, ventilation, wind degree, wind speed, will be used in the upcoming work to monitor the broiler welfare and health. The water consumption patterns of broiler chickens are particularly interesting concerning flock welfare health and flock resilience. This will be further studied and demonstrated in the case study, where data on water consumption patterns of broiler flocks are collected, and new or improved algorithms will be developed to use generated data, which are until now collected by many farmers but not used in an optimal way. The following sub-questions will be answered in this case study:

- (1) Determine whether the circadian pattern in drinking behaviour is predictive of flock resilience and how this depends on conditions during hatch (hatching in light vs. darkness and with or without early feeding) and the light schedule during rearing. This is based on the hypothesis that in cattle stable circadian rhythms in activity were predictive of resilience and the fact that circadian rhythms are already established in chicken embryos.
- (2) Whether deviations in drinking patterns, together with other parameters that (depending on the facilities installed) might be available, can be used as early indicators of disease in broiler flocks, to determine sickness behaviour in a very early stage preventing further spread of disease.
- (3) Study the views of farmers and other stakeholders towards the use of an AI-based tool of water consumption (combined with data of other available facilities) and how this can improve their management. This includes an analysis of barriers and opportunities for the application of the tool by stakeholders.
- (4) Explore end-consumer perceptions of products produced with data-driven tools, acting as an objective, data-driven source of information.



Sources:

a) landbouwtelling CBS 2022 (www.statline.cbs.nl)

b) Netto-export (export-import) van broedeieren en broedeieren ingelegd voor export als eendagskuiken

c) Nevedi, Nederlandse Vereniging Diervoederindustrie Cijfers 2022 (www.nevedi.nl/feiten-cijfers)

d) COBK Leden van de Centrale Organisatie Broedeieren en kuikens: 13 locaties van 10 bedrijven.

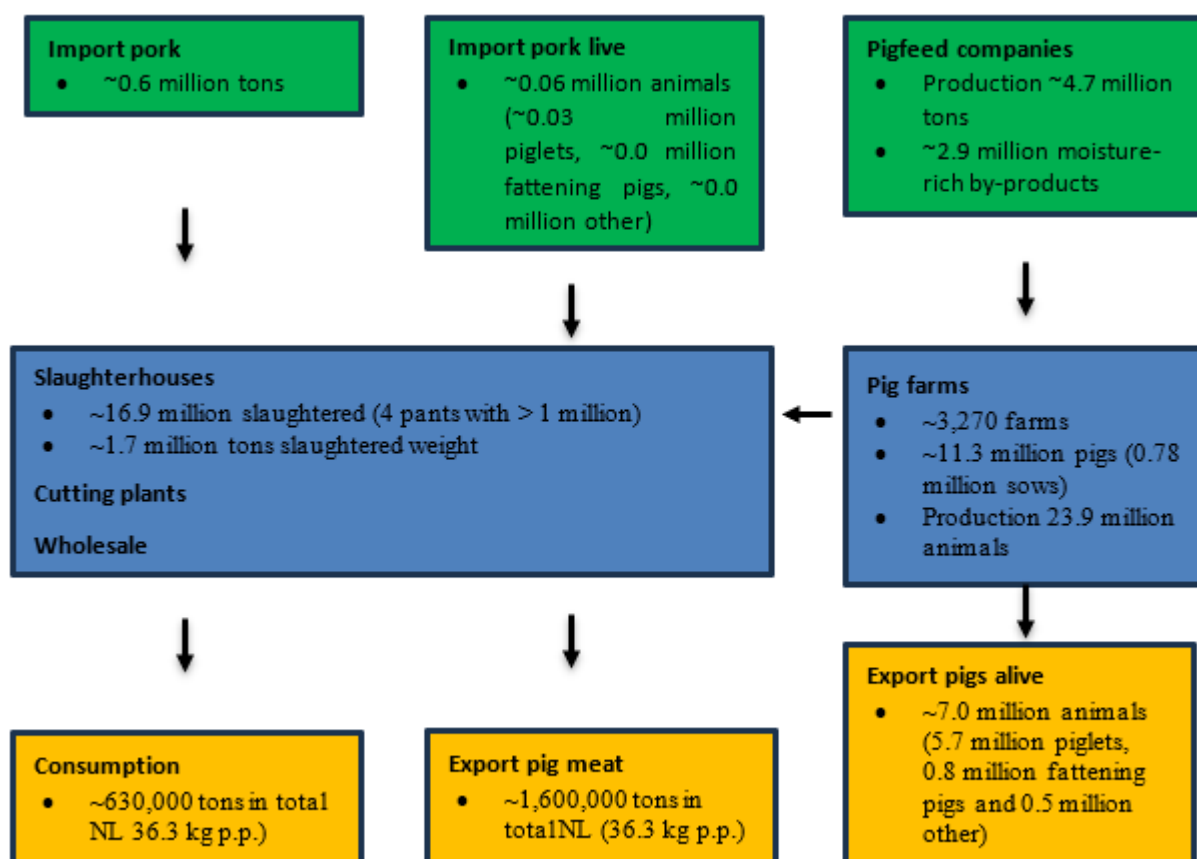
e) Nepluvi Jaarverslag 2022 Vereniging van Nederlandse Pluimveeverwerkende Industrie: 14 locaties, 8 bedrijven

f) Voorzieningenbalans vleeskuikens, 2022 (www.agrimatie.nl/voorzieningenbalansen)

g) In- en uitvoer productgewicht omgerekend naar geslachtgewicht

Figure 2. Flow chart of the organization of the Dutch broiler sector 2022 (Berkhout et. al., 2024).

This case study will be a collaboration between researchers, an AI company for data analysis, farmers, and veterinary practices and slaughterhouses. In case study A, the pig value chain will also be explored. Thereby, animal welfare data to increase transparency on pig welfare in the production chain will be explored. Data from slaughter plants will be considered. Data will be obtained from the slaughter plant and will be used to develop AI tools as already developed and partly integrated within the EU-funded aWISH project. We will demonstrate the value of these automatically generated welfare data to improve animal welfare information from the pig production chain in close collaboration with partners of the aWISH project. We will analyse barriers and opportunities for increased application of the tool from the stakeholders' perspective. Case study A is linked especially to case studies C and E, but it also supports case study B, as further described in later sections of this deliverable.



Sources: CBS, FEFAC, OPNV, ~~bewerking~~ Wageningen Economic Research

Figure 3. Flow chart of the organization of the Dutch pig sector 2023 (Berkhout et. al., 2024).

Materials and methods

The broiler sector is a well-organized sector. Broilers from the hatchery become ready for slaughter in a period of about 6 weeks. The fattening of the chicks can be divided into several phases:

1. ~1-3 days
2. ~4-11 days
3. ~12-23 days
4. Period until unloading the first part of the flock
5. Period until unloading the rest of the flock

The water supply is a crucial aspect with regards to the fattening of broilers. For this reason, the water supply to the birds is monitored on every broiler farm. The water supply monitoring is mainly used as a technical parameter to be able to quickly signal system malfunction. However, a management system has been developed that frequently (for example 4 times per hour) reads waterflow measurements per stall from the process control systems and checks whether there are intake deviations compared to what is expected based upon the previous period. If there is a deviation that cannot be explained by other parameters (such as lighting settings and stable temperature), the poultry farmer is alerted.

In case study 3.1 of the Digi4Live project it is researched whether water intake data can be used to:

- A. Investigate whether there is a circadian rhythm in the daily water intake characteristics of the broilers;
- B. If there is indeed such a rhythm, can the information be used to make an estimate of the flock resilience.

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C. Detect diseases and health problems in an early stage:

- Hypothesis: flocks with systemic diseases or intestinal health problems show anomalies in water intake
- Locomotion problems
- Contact dermatitis: affecting the skin of the soles of the feet, heels and chest
- Restriction in natural behaviour
- Heat stress
- (Intestinal) health
- Interaction between hereditary traits and environment

Historical data was received from 4 broiler farms. The data of those farms can be used gaining insight into the data profiles, but the data in this form is less suitable for (static) analyses.

The actual study is based upon research information of 5 broiler farmers which have in total 40 stalls. On those farms several breeds are kept. The water flow data of different flocks is recorded over a period of at least 3 months (≥ 2 flock periods per stall) together with other available process data. From each flock, also vaccination, medication and mortality data are collected.

On the farms, a management system is installed to interface the on-farm process control systems. The data downloading is a continuous process. The farmers are invited to use the management system in their day-to-day farm management. In the research the management system of the farms is used for monitoring purposes, e.g. for signalling irregularities. The farms are consulted by study's employees on a regular basis.

The water data are recorded together with data relating to vaccination, medication, mortality and other details over the lifespan of the flock. The water intake will be analyzed based on:

- Daily water intake pattern (percentage of water intake during 15 minutes compared to the total 24 hour intake) and
- Lifespan intake pattern (daily water intake throughout broiler life),

The analysis focuses on the 5 fattening periods of broilers, especially focusing on the 2nd and 3rd period (~4-11 days and ~12-23 days), in the 1st period there is not yet a steady state situation making the possibility of signalling deviations un-useful and in the 4th and especially the 5th there are very limited or no possibilities for the farmer to intervene.

First results

The first results are based upon historical data received from 4 broiler farms:

- 2 farms with 4 stables each and data from 2 cycles,
- 1 farm with 1 stable and 2 cycles,
- 1 farm with 8 stables and 2 cycles (however, the first datasets are incomplete and hence unusable).

Based on the data daily and lifespan intake profiles were created. The figures 1 to 3 show the intake profiles that were created based upon the data (of farm G, with 4 stalls with all 4 having 2 broiler fattening rounds). In Figure 4 the average percentages of water intake per 15-minute period relative to full 24-hour intake for the overall period, and of the 5 different phases are presented. In Figure 5 the profiles of the average of the 1st and last (5th) phase have been left out. In Figure 6 the average water intake per broiler per day of age is presented for farm G, with a distinction between the period until unloading and from unloading onwards.

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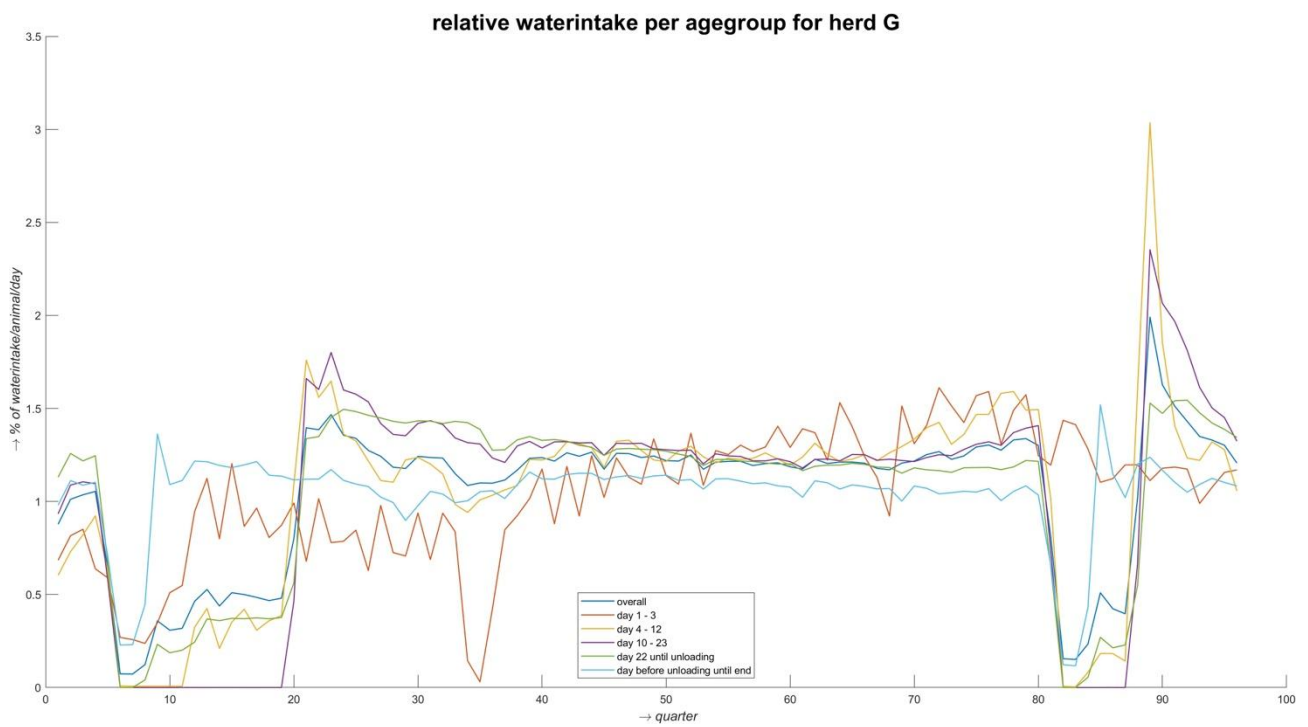


Figure 4. The percentage of water intake by quarter compared to full 24-hour intake of farm G overall and for the 5 different phases.

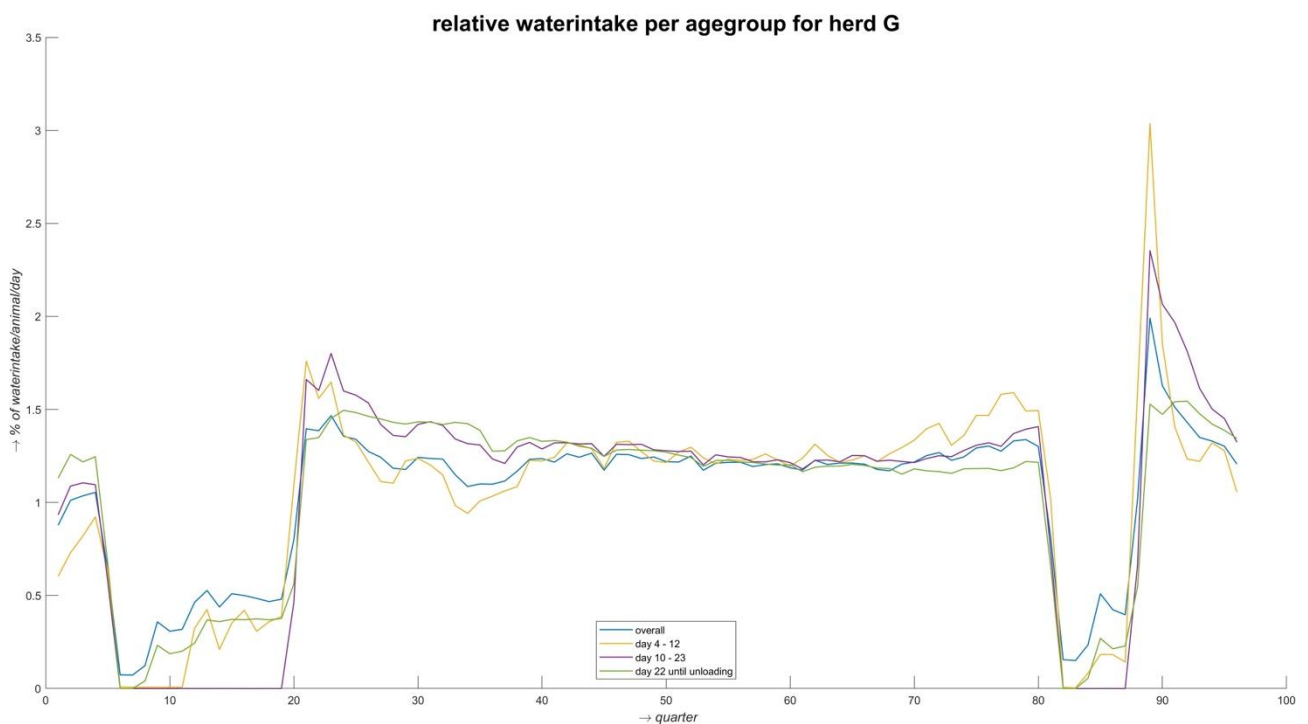


Figure 5. The percentage of water intake by quarter compared to full 24-hour intake of farm G overall and for the 2nd, 3rd and 4th phase.

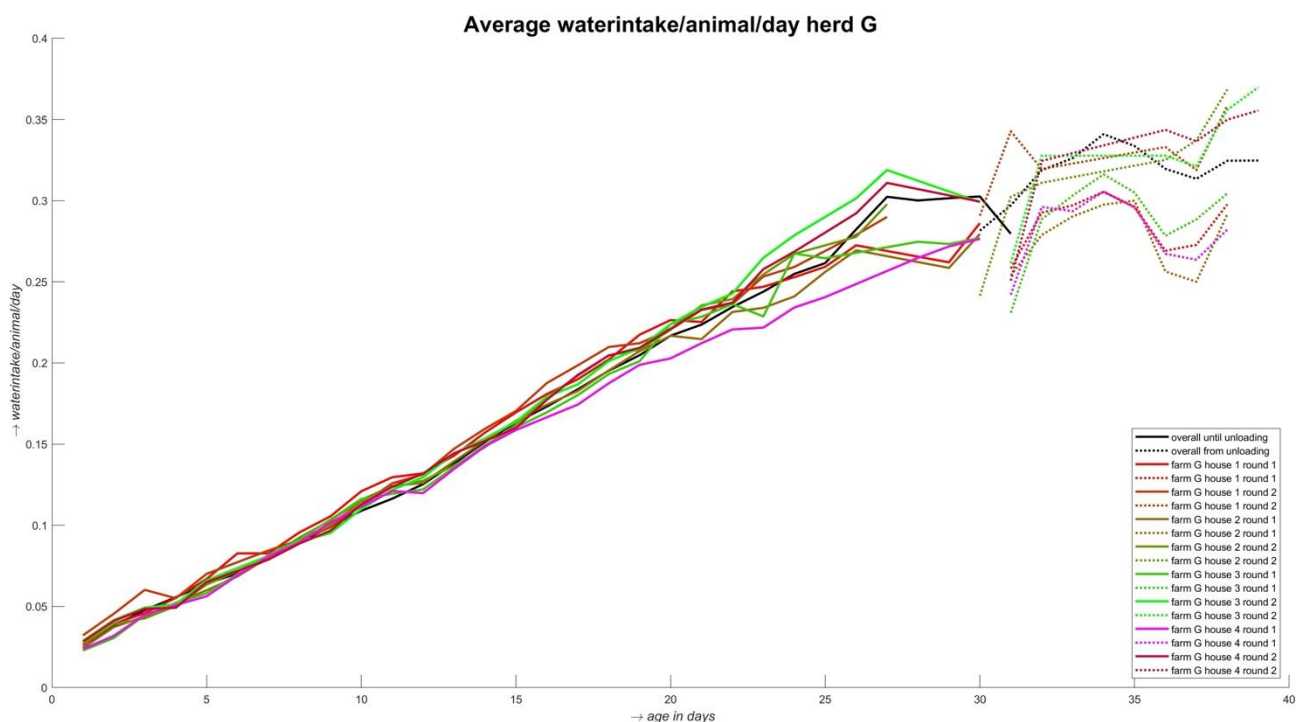


Figure 6. The average water intake by broilers' age in days for all groups and rounds and for the individual 4 groups and 2 rounds of the broilers of farm G.

Discussion and future plans

The average percentage of water intake profiles (see figure 5) give an overview of the broiler drinking activities during the day. In the graphs the two periods during the day where the lights are switched off can be seen for all the different phases.

The figures show that there is some drinking activity even during the periods where normally the lights are switched off. The explanation for this is: during the fattening period the farmer might have worked with a shorter light off period during some days to allow the broilers more time to eat and drink so that the animals can take in enough energy to keep up with the growth rate without going into hypoglycaemia.

The average water intake per 24 hours over the entire period gives an overview of the increasing amount of water a broiler on the average daily drinks during its lifetime. It is expected that the daily and lifespan intake patterns can be good bases for researching the existence of a circadian rhythm in the daily water intake characteristics of the broilers and they are also expected to be a basis for detecting health and welfare problems in an early stage.

Of the farms from which the water intake profiles were received, no information was yet received regarding vaccinations, treatments, mortality and other comments. This makes the data suitable for gaining insight into the data profiles, but the data in this form are less suitable for statical analyses. Therefore, we worked on getting online access to farm water intake profiles and to have an agreement with those farmers to also have access to the additional information of those farms (flocks). In total 5 broiler farmers having in total 40 stalls have been found and are prepared to cooperate with the project. The management software has been installed on those farms and the data collection will be started when new flocks arrive on those farms.

In the next phase, we will collect data on water intake profiles and related sensor data via the developed management tool for at least two complete rounds per stall, and collect information regarding thinning, vaccinations, treatments, mortality and specific welfare-relevant notifications from the farm administration.

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Circadian rhythmicity of and anomalies in the water intake profiles are linked to the health parameters of the flocks, to validate if water intake profiles indeed are useful to monitor health and welfare. Moreover, we collect feedback from the farmers that use the tool about its usability. The case study will help to validate the model and quantify its practical value. The results will be shared with the private sector actors through news items in professional publications.

3.2. Description of case study B: Resilience and transparency

Aims and background

This case study aims to enhance the resilience and transparency of livestock supply chains through the integration and effective use of diverse data types in the TRACES (Trade Control and Expert System) platform. By improving data flow throughout the entire transport process—from initiation to completion—the case study adopts a logistics-centred approach, focusing on transport-specific challenges. It proposes innovative solutions for better data utilisation, including **ready-to-go reports** and **active online information tools**, and emphasises cross-country learning between Poland and Denmark, paving the way for scalable and harmonised applications across the EU.

TRACES serves as a key EU platform for managing the movement of animals and animal products in the EU, facilitating documentation, certification, and coordination among stakeholders. However, the system currently faces limitations such as fragmented data systems, non-live verification, and substantial administrative burdens. These issues reduce its capacity for real-time monitoring and transparent decision-making.

The EU works on enhancing TRACES with features like live welfare monitoring of animals during transport and environmental impact tracking for product movements. This case study will explore how these advancements can be realised. The case study has a dual focus:

- **Live animal transport:** Concentrating on welfare aspects, including stress levels, temperature, humidity, hydration, and rest intervals.
- **Product transport:** Addressing environmental issues such as emissions, fuel efficiency, and transport route sustainability.

By leveraging Poland's and Denmark's unique contexts and experiences, the study aims to foster learning between the two countries, enabling mutual adaptation of best practices and ensuring that proposed solutions are robust, replicable, and scalable.

The case study brings together partners and actors with expertise in transport logistics, digital technologies, and animal welfare:

1. **Instytut Genetyki i Biotechnologii Zwierząt (IGBZ) - Poland:**
 - Focus on poultry and cattle transport.
 - Leads efforts to integrate welfare monitoring tools and GPS tracking with TRACES, emphasizing Poland's regional transport dynamics.
2. **Danish Technological Institute (DTI) - Denmark:**
 - Specializes in primarily pig transport, though digital tools from the competent authority handle every livestock species in Denmark.
 - Develops automated systems for environmental data collection and online tools for real-time monitoring and reporting, incorporating Denmark's advanced digital infrastructure.
3. **Collaborative Stakeholders:**
 - Public and veterinary authorities in Poland and Denmark.
 - Farmers, transport operators, and processors, providing insights to validate and refine solutions.

D3.2 Case studies follow-up report

The study addresses species-specific transport needs of pigs in Denmark, as well as poultry and cattle in Poland.

Proposed enhancements within this Case study are overall:

- **Ready-to-go reports:** Automatically generated summaries from collected data, tailored for regulatory authorities, transport operators, and policymakers, streamlining compliance checks and improving decision-making.
- **Active online information tool:** An interactive platform providing live updates on transport status, welfare indicators, and environmental metrics, enabling stakeholders to address issues in real time and improve transparency.

Finally, this case study facilitates a mutual learning process between Poland and Denmark, leveraging the unique strengths and challenges of each country.

- **Poland:** Insights from regions with varying transport conditions, particularly at the EU's eastern borders, where cross-border dynamics and resource constraints shape the transport landscape.
- **Denmark:** Advanced digital systems and a strong regulatory framework provide a model for integrating technology into TRACES and optimizing environmental monitoring.

The expected outcomes of this case study are a concept of an automated data handling for animal and product displacements, reduced burden on the actors, improved control of animal welfare and environmental impacts of the intra-EU transports, control of each carcass, improved transparency and communication (producers, processors, consumers). The study's findings and proposed solutions are designed to be scalable across the EU, offering a roadmap for harmonised transport data systems. The integration of welfare and environmental monitoring tools, coupled with streamlined reporting and active online tools, creates a robust framework for replicability. By aligning with the EU policies and leveraging the cross-country collaboration between Poland and Denmark, the study ensures that its solutions can address the diverse needs of EU member states while supporting sustainability, resilience, and transparency in livestock supply chains.

Materials and methods

In CS-B we address the key risks and considerations for live animal and animal product transport, with a particular focus on Poland and Denmark. The primary aim is to integrate animal welfare-sensitive route planning into TRACES as impacted by environmental parameters. This methodological approach is designed to identify and mitigate heat stress risks while transporting live animals and issues in chilled products transport by integrating planned logistics data from the TRACES platform with centralised forecasted weather conditions.

Live animals

Transporting live animals exposes them to environmental stressors, particularly thermal extremes. Exposure to high or low ambient temperatures—especially when combined with humidity, transport duration, and loading density—can severely affect animal health and welfare, potentially resulting in in-transit mortality or increased post-transport morbidity.

Species such as broilers are particularly vulnerable due to high metabolic rates and low tolerance to heat, but all species are affected by the above parameters. Dead on arrival (DOA) rate is a widely used animal welfare indicator that quantifies the percentage of animals that die during transport and are found deceased upon arrival at their destination, typically a slaughterhouse or an inspection point.

Chilled animal products

Similar stressors apply to the transport of temperature-sensitive animal products such as meat and dairy products. These products require uninterrupted refrigeration to maintain food safety and quality standards.

D3.2 Case studies follow-up report

An indicator during transport which measures the proportion of goods rejected at delivery due to temperature-related spoilage or contamination is product loss rate. It is derived from comparing shipped volume versus accepted volume at processing or retail facilities.

Heat stress

Methodology for predicting heat stress is based on using planned route in TRACES and weather forecast (not real current conditions) to predict heat stress, as measured and identified from the literature during transport. This information can be used to propose a route that is the most effective for birds' welfare.

Data Sources

Logistics data

Route plans, departure times, expected arrival times, and geographic coordinates of the journey segments were extracted from the TRACES platform. These data included all declared waypoints, vehicle types, animal densities, and declared transport duration.

Weather forecasts

Short- and medium-term weather forecasts were obtained from meteorological services such as the European Centre for Medium-Range Weather Forecasts (ECMWF) and local sources (e.g., Meteo.pl or <https://opendatadocs.dmi.govcloud.dk/DMIOpenData>). Forecasted variables included:

- Ambient temperature (°C)
- Relative humidity (%)
- Solar radiation (W/m²)
- Wind speed (km/h)

These forecasts were time- and location-matched by the expected position of the transport at hourly intervals.

Risk modelling

Each transport route is divided into time-stamped segments corresponding to planned waypoints. For each segment, a Temperature-Humidity Index (THI) is calculated using the formula:

$$THI = T - (0.55 - 0.0055 \times R) \times (T - 14.5)$$

Where T is the ambient temperature in Celsius degrees and R is the relative humidity in percent. This formula accounts for both the direct effects of temperature and the compounding influence of humidity, which affects animal thermoregulation.

Species-specific thresholds are applied to interpret the THI scores. These thresholds are informed by existing scientific literature such as EFSA and the work of Mitchell and Kettlewell (2009). Typically, THI values below 24 are considered low risk, values between 24 and 27 are moderate risk, and values equal to or exceeding 27 represent a high risk of heat stress. These risk classifications are then assigned to each segment of the transport route to create a cumulative Heat Stress Risk Index (HSRI) for the full journey.

Following each modelled or real transport event, a detailed report is compiled. This report includes a segment-by-segment classification of HSRI, an overall mean THI for the trip, and an estimated DOA rate based on historical correlations derived from regression models. Additionally, a geographic visualization of high-risk segments is prepared.

For the transport of chilled animal products such as meat and dairy products in addition to eggs, the methodology focuses on evaluating cold-chain stability. The key metrics assessed are the mean transit

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temperature, the number and cumulative duration of temperature excursions outside the target range (commonly 0–4°C), and the maximum deviation from the defined threshold. These factors are analysed to calculate a Cold Chain Integrity Score (CCIS), which serves as a standardised risk measure for product spoilage.

Optimization and decision support

To support informed and welfare-conscious decision-making in livestock and chilled product transport, the collected and forecasted data are processed through a multi-objective optimization framework. This model simulates alternative transport scenarios by adjusting two key operational variables: the scheduled departure time and the geographic route. Departure times are flexibly shifted within a ± 3 to 6-hour window to evaluate the impact of avoiding periods of extreme heat or cold. Additionally, alternate routes are tested with a constraint that the total distance does not exceed a 20% increase over the original route, ensuring realistic operational feasibility.

The optimization algorithm evaluates each scenario against a set of core objectives. For live animal transport, the priority is to reduce welfare risk, particularly by minimizing exposure to thermal stress, which is quantified through the previously calculated Heat Stress Risk Index (HSRI). For the transport of chilled animal products, the model focuses on maintaining the integrity of the cold chain, minimizing temperature excursions and deviations that could lead to spoilage. In all cases, the model also considers practical logistics constraints such as overall transport time, fuel consumption, and the risk of penalties from late deliveries due to contractual obligations.

Each generated scenario is assessed using a composite scoring system that integrates these variables into a single decision-support metric. The results are then visualized to facilitate interpretation and stakeholder engagement. These tools will aim to guide transport planners, animal welfare officers, and policy actors in selecting the most balanced and effective transport options.

Data integration and storage under development

To ensure the scalability, transparency, and future interoperability of the developed tools and models, all datasets used and produced will be formatted according to the FAIR principles—Findable, Accessible, Interoperable, and Reusable. This guarantees that the data can be reused by stakeholders across projects, sectors, and Member States, and can be seamlessly incorporated into existing data ecosystems.

First results

The initial results of Case Study B reflect progress in methodological development and conceptual modelling, laying the foundation for future data integration. A major outcome of the first phase has been the development of a predictive model that integrates transport logistics from TRACES with forecasted weather conditions to estimate welfare risk for live animals during transport (Table 1). This includes the formalization of the Temperature-Humidity Index (THI) and the establishment of species-specific Heat Stress Risk Index (HSRI) thresholds, informed by existing scientific studies and adapted for poultry, pigs, and cattle. An important step was also the identification of key welfare and quality indicators. For live animal transport, DOA rate was confirmed as the central outcome metric for assessing welfare impact. For chilled products, such as poultry meat and eggs, CCIS was defined to capture the severity and frequency of temperature excursions during transport, based on exposure duration and deviation from target ranges.

In addition, the study defined operational parameters and thresholds for dynamic transport optimization. These include allowable route variations (not exceeding 20% in distance), realistic departure time adjustments (± 3 –6 hours), and scenario constraints accounting for logistical feasibility, fuel consumption, and contractual delivery obligations. An initial simulation framework was created to assess the trade-offs between welfare risk reduction, environmental impacts (particularly CO₂ emissions), and transport efficiency.

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The case study also identified systemic gaps within the current TRACES implementation. Despite TRACES serving as a centralized logistics and certification platform, no current mechanisms exist within the system for incorporating forward-looking welfare analytics such as weather-based risk modelling or product-level environmental controls. A key finding was the absence of mechanisms for integrating forecast data into real-time route planning, limiting the system's ability to proactively prevent animal welfare risks. There is no infrastructure within TRACES to capture and process product-level telemetry data for temperature-sensitive goods, despite evidence of its relevance for food safety assurance.

An example scenario

This scenario applies the Case Study B methodology to a real-world inspired example of long-distance beef cattle transport from Olsztyn in Northeastern Poland to Clermont-Ferrand in Central France. The shipment consists of 32 beef cattle, each animal weighing 600–700 kg, transported over a 1 700 km journey, requiring compliance with EU welfare regulations, including mandated rest stops.

The original transport plan schedules departure at 10:00 on August 3rd, traversing the route through Germany and Northern France, with scheduled rest breaks in Leipzig and Reims. Based on weather forecasts from the ECMWF, daytime temperatures are expected to peak at 33°C near Leipzig and 34°C in Reims, with relative humidity around 55%. To evaluate animal welfare risk, the THI is calculated for each route.

Applying this for Leipzig ($T = 33^{\circ}\text{C}$, $\text{RH} = 55\%$) results in a THI of 28.4. A THI above 27 indicates moderate-to-high heat stress for beef cattle. The result in Leipzig confirms that this stop would expose animals to substantial thermal stress. A similar calculation for Reims ($T = 34^{\circ}\text{C}$, $\text{RH} = 55\%$) yields a THI of approximately 29.1, further supporting the risk classification. With these segments classified under the Heat Stress Risk Index (HSRI) as “high risk,” the scenario simulation estimates the Dead-on Arrival (DOA) rate to be approximately 1.1%, based on species-specific regressions derived from past transport data and literature.

Figure 7 presents a comparative visualization of original and optimized beef transport routes from Poland to France, including rest stops, estimated temperatures, and heat stress risk zones. Optimized timing avoids peak heat exposure to reduce animal welfare risks. An optimized transport scenario is proposed by adjusting the departure time to 02:00 on the same day. This change shifts travel through risk zones to cooler hours. The new rest points are moved to slightly southern locations where early morning temperatures are around 21–26°C. Differences in the THI and the respective estimated temperatures can be seen in the table 2 below.

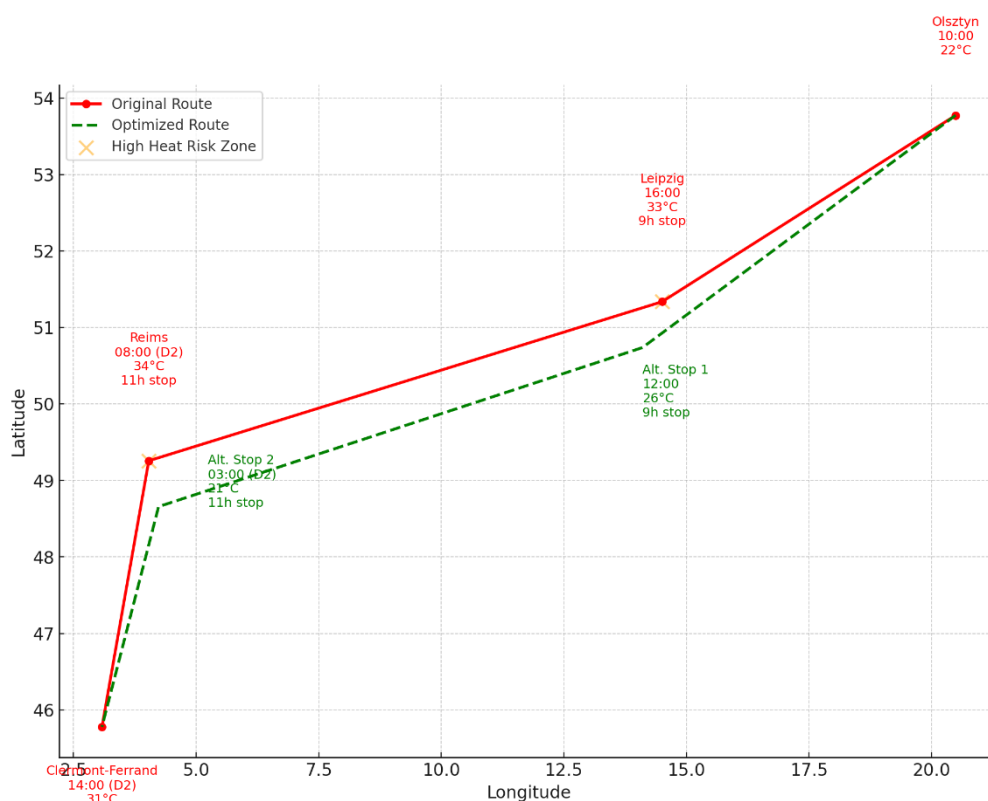


Figure 7. A route example from Olsztyn (PL) to Clermont-Ferrand (FR) with time stamps and temperatures (in °C) at the planned stops compared to an alternative temperature-optimized route.

Table 2. Calculated THI based on a base 55% relative humidity (RH) and specified temperatures for the routes illustrated in Figure 8.

Stops	Non-optimised route THI (Temperature, Relative Humidity))	Temperature optimised route (THI (Temperature, Relative Humidity))
Olsztyn	20.14 (22, 55%)	20.14 (22, 55%)
Leipzig / Alt. 1	29.17 (26, 55%)	23.15 (26, 55%)
Reims / Alt. 2	28.42 (33, 55%)	19.39 (21, 55%)
Clermont-Ferrand	26.92 (31, 55%)	26.92 (31, 55%)
Average	26.16	22.40

D3.2 Case studies follow-up report

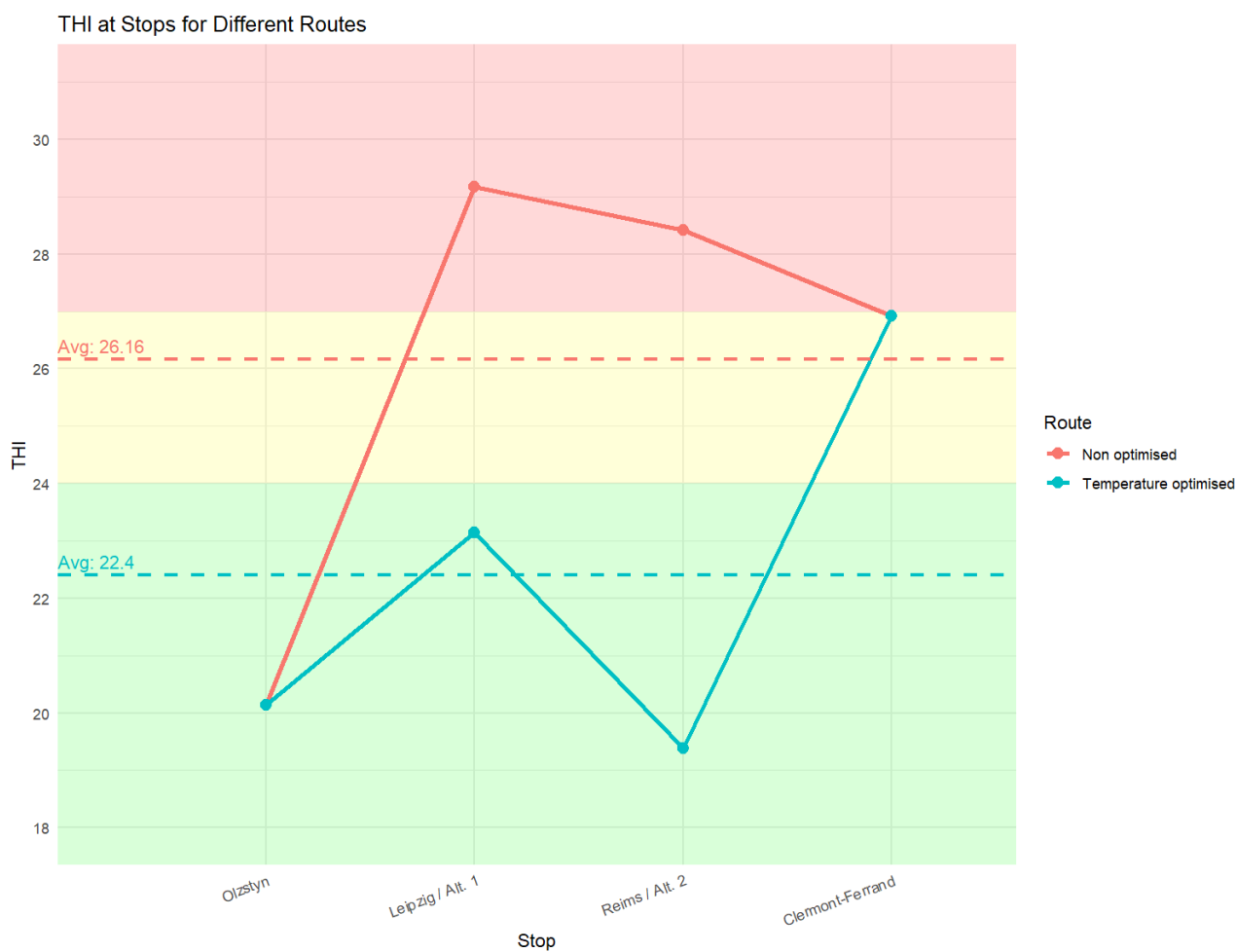


Figure 8. Demonstrating the routes in terms of the risk of heat stress. Low risk (green zone), moderate risk (yellow zone) and high risk (red zone).

The optimised THI value falls well below the risk threshold, reducing predicted welfare stress. The DOA rate is recalculated under the optimized scenario to be only 0.3%, reflecting an estimated 72% reduction in mortality risk. Despite maintaining the same travel duration and regulatory compliance (28 hours with 9h and 11h stops), the temporal shift greatly improves animal welfare outcomes.

Both scenarios are visualized with route sketches, THI overlays, and stop duration indicators in addition to the summarised THI table. Heat zones are identified along the original route, while the optimized scenario demonstrates effective avoidance of these risks. Emissions and fuel usage remain similar between routes, but the optimized scenario incurs a minor cost for night labor (~€120), which may be outweighed by the welfare benefit.

Discussion and future plans

The first step of this case study was to identify development gaps within the TRACES system. It became evident that while TRACES facilitates logistics and certification, it lacks features for live animal welfare tracking during transport. There is currently no integration of predictive tools such as weather-based route optimization which could reduce thermal stress or related environmental impacts like emissions. Similarly, monitoring of chilled animal products remains outside the system's scope, limiting the case study's focus primarily to live transport. Although the case study has proposed a model to link TRACES data with weather forecasts and welfare indicators, this tool cannot be directly integrated with TRACES because it is a closed system managed by DG SANTE.

D3.2 Case studies follow-up report

In the next phase, a series of simulated transport scenarios will be conducted using TRACES data enriched with weather forecasts. These simulations will calculate predicted heat stress risk, DOA rates, emissions, and operational costs across alternative routes and timings. The results will help validate the model and quantify its practical value.

3.3 Description of case study C: Robust AI methods for sensor-based animal tracking

Aims and background

Case Study C aims to develop an AI-driven adaptive tracking system for pig and dairy cow production chains, with the core objective of enhancing the robustness of AI models to ensure stable performance under diverse environmental conditions. The study focuses on two specific use cases: i) analysing video data using computer vision technologies to track group-housed pigs and generate animal welfare Key Performance Indicators (KPIs); and ii) utilising sensor-based grazing data to ensure compliance with the production requirements of Maroilles PDO cheese (Figure 9).

Given the high sensitivity of these AI systems to environmental variations, external conditions can significantly impact their reliability in generating pig welfare KPIs and tracking outdoor activities for dairy cows. To address this challenge, Case Study C will focus on improving the adaptability and resilience of AI models across diverse indoor (pigs) and outdoor (dairy cows) conditions, laying a solid foundation for their broader application in practical production scenarios.



Figure 9. Case study C use cases: computer vision on pigs and sensor-based grazing traceability on dairy cows.

To achieve these goals, Case Study C will undertake the following activities:

1. **Evaluate AI model performance under varying field conditions:** Assess the strengths and weaknesses of AI models in diverse environmental scenarios and optimise them accordingly.
2. **Develop active learning techniques to improve labelling accuracy:** Introduce smart labelling processes to enhance the efficiency and accuracy of data annotation through active learning, reducing the need for manual intervention.
3. **Investigate the transferability and scalability of deep learning models:** Explore how deep learning models can be transferred and scaled across different animal tracking scenarios to enhance the system's generalisability.
4. **Leverage synergies between computer vision and sensor-based tracking:** Investigate the collaborative potential of computer vision and sensor-based tracking technologies, focusing on scalability across species and use cases, while exploring interconnections with case studies A and E.
5. **Engage stakeholders:** Gain insights into stakeholders' needs and expectations to guide the development of future services.

D3.2 Case studies follow-up report

Case study C has provided robust support for the Digi4Live project in ensuring animal welfare and advancing digital farm management within the livestock production chain. By addressing a series of key challenges, such as how to maintain model reliability in diverse and complex indoor and outdoor environments? How to optimize data annotation using active learning techniques? How to enable model transferability and scalability across different application scenarios? How to meet stakeholder needs through technological innovation? And how to seamlessly integrate this system into existing farm animal monitoring systems?, Case Study C aims to enhance the robustness of AI-based tracking systems, offering valuable insights for practical applications in pig and dairy cow production.

Furthermore, case study C aims not only to improve the reliability of real-time animal tracking data within the production chain but has also advanced the development of traceability systems for end-products and food safety frameworks. By providing data-driven evidence for decision-makers, it has further contributed to the creation of intelligent, data-driven livestock production chains, laying a solid technical foundation for the sustainable development of modern livestock farming.

Materials and methods

Pig tracking with computer vision

Computer vision has become a promising tool in digital phenotyping and Precision Livestock Farming (PLF). Depending on the application, different types of visual representations - namely object detection, pose estimation, and segmentation - serve as the core components of the entire monitoring system.

Designing transferable and scalable pig monitoring system across diverse farm environments requires computer vision models with high representation capacity and strong generalization ability. In practice, this often entails deeper networks, more parameters, and extensive training data—all of which contribute to increased model complexity and computational demands. However, such designs conflict with the practical constraints of PLF, where models must operate in real time on low-cost, resource-limited hardware. This conflict underscores a key challenge in real-world deployment: What strategies can improve the transferability of lightweight models in heterogeneous environments?

In Digi4Live, we addressed these issues by proposing a modular design that decouples environmental variations from individual animal variability. At the framework-level, we introduced a Rotated Bounding Box (RBB) detector combined with active learning strategy to achieve seamless scene adaptation.

Grazing traceability

The traceability of dairy cow grazing, particularly the estimation of grazing time, can be achieved through the use of GPS collars combined with tailored prediction models. This approach has been previously explored (Fischer et al., 2021; Allain et al., 2021).

In this case study, the system consists of GPS collars fitted to dairy cows and a companion digital application called Chronopâtûre. This application allows farmers to visualize animal movements in real time and facilitates data extraction (Figure 10).

The grazing traceability system has been implemented on five farms located in northern France. This deployment was designed to collect data under a range of real-world grazing conditions, including unrestricted and restricted pasture access, varying grazing strategies, and different paddock sizes. The collected data will serve these key purposes:

- Validation of the current system: The tool's accuracy will be evaluated by comparing its outputs against reference data manually recorded by farmers on each participating farm.
- Model Improvement: The data will be used to refine the existing prediction models for estimating grazing time. This includes addressing gaps in GPS data, correcting positional inaccuracies, and improving the identification of grazed paddocks.

D3.2 Case studies follow-up report

- Assessment of model transferability: The project will explore how well the current model performs under different environmental and management conditions, to evaluate its generalizability.
- Development of new services: Leveraging the collected data, new digital services will be developed for farmers, dairies, and PDO cheese organizations. These may include interactive grazing maps, heatmaps to visualize grazing pressure, and automated tools for generating grazing calendars.

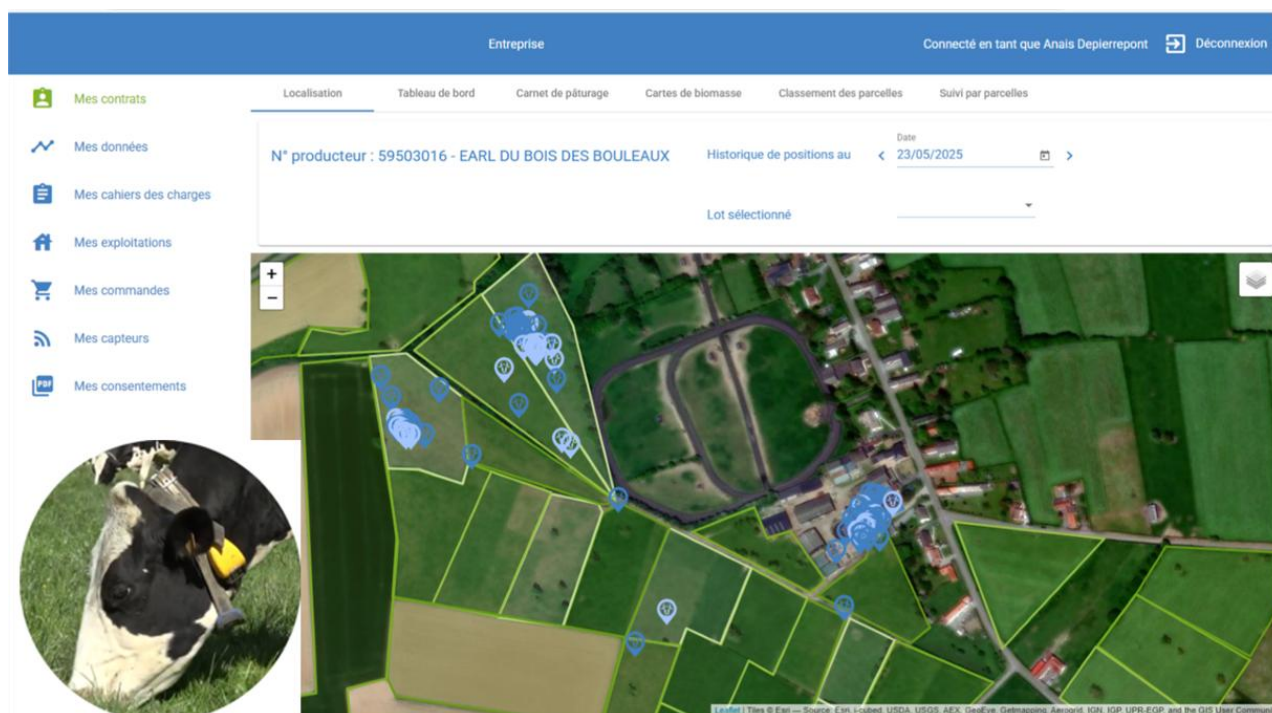


Figure 10. Chronopâtûre grazing traceability tool used in the case study C.

First results

Pig tracking with computer vision

The results concerning pig tracking with computer vision can be summarised under three points as follows:

1. Raw video from 30+ farms have been recorded (including existing data and three new stakeholders).
2. Dataset (version 1) has been annotated for five computer vision tasks (object detection, body keypoints detection, segmentation, posture estimation and multi-objects tracking). These labelled datasets are used for the development of Smart Labelling Loop and transferable algorithms.
 - Pig detection dataset (3000+ images cross 30+ different environment).
 - Pig keypoints, mask and posture dataset.
 - Pig tracking dataset.
3. A peer-reviewed paper *MT-SRnet: A Transferable Multi-Task Super-Resolution Network for Addressing Pig Keypoints, Mask, and Posture* (Liu et al., 2025) was published in Computer and Electronics in Agriculture. In this paper, we made progress in transferability and scalability of existing methods across diverse farming environments. At the framework-level, we introduced a Rotated Bounding Box (RBB) detector combined with an Auto-Visual Prompt strategy to effectively suppress background interference and achieve seamless scene adaptation. At the task-level, we developed a Multi-task Super-Resolution Network (MT-SRnet) capable of simultaneously predicting pig keypoints, masks, and postures from low-resolution inputs. Our experimental results demonstrate that MT-SRnet maintains high accuracy (Keypoints - 95.33% mPCK; Mask - 95.53% mIoU; posture - 89.72% accuracy) while substantially reducing model complexity by over 30-fold. Moreover, the proposed approach achieves a substantial increase in inference speed (up to ~17,000 pigs/s), highlighting its practical suitability for real-time monitoring under resource-limited conditions.

Grazing traceability

Data collection and local project coordination were carried out in close collaboration with key stakeholders, including farmers, dairies, the Maroilles Cheese Organization, and the technology provider Chronopâtûre. To ensure stakeholder engagement and sustained motivation, four dedicated meetings were held throughout the project. Raw GPS data were collected during the grazing season across the five participating farms, over 2 years. This data collection aims to capture variability in grazing practices and environmental conditions.

The initial phase of data analysis has just begun. It focused primarily on visualizing the raw data and assessing the spatial extent of pasture use by the cows (see Figure 11). These exploratory analyses serve as a foundation for further, more detailed modelling work.

Additionally, a presentation titled “A Review on Implementational Gaps and Barriers Regarding Data Quality and Robustness for AI Applications in Livestock Digital Solutions” was delivered at the EAAP AI4AS (Artificial Intelligence for Animal Sciences) session. This presentation highlighted the critical challenges related to data quality and robustness in digital livestock tools. Using the grazing traceability case study, it explored both the limitations currently faced and the potential solutions for improving data reliability and AI model performance in such applications.



Figure 11. Cow positions on one farm and one week and grazing area covered.

Discussion and future plans

Pig tracking with computer vision

The transferability and scalability of computer vision algorithms are essential for cross-scenario deployment in the field of precision livestock farming and digital animal phenotyping. However, maintaining scene adaptation capabilities in a lightweighted vision system presents a notable conflict between model capabilities and inference latency. The first result has made progress in addressing this conflict by adopting modular design principles and offers various benefits, two of which are elaborated below.

We first discussion point is **task decomposition and specialization**. The overall pig monitoring system is divided into sub-tasks, each handled by a specialized module. The RBB detector functions globally, understanding the entire pig house. Its role includes identifying pig presence and suppresses background variation. Combined with the proposed Auto-Visual Prompt, the learning process is simplified by explicitly directing sub-modules' attention to pig-specific regions, enabling the model to extract crucial features for each subtask. Scene adaptability. The proposed Auto-Visual Prompt ensures that a relatively small dataset can adequately approximate the entire spatial characteristics of pig images. Consequently, when working with varied datasets or transitioning to a new environment a straightforward adjustment to the detector is adequate for seamless scene adaptation for the entire vision system.

The second aspect concerns **flexibility**. As the complexity of the entire system grows, additional modules can be smoothly integrated and support new functionalities, e.g., body condition scoring, weight estimation, behavioural quantization. Despite the promising experimental results, our method has a notable limitation in that it does not fully address the transferability and scalability of the entire monitoring system. The next focus will be Smart Labelling Loop development to ease the data annotation and scene adaptation challenges.

Grazing traceability

One of the main challenges associated with GPS data in grazing systems lies in the presence of gaps, particularly when cows are inside barns, and inaccuracies in recorded positions (Lebreton et al., 2022). These issues are highly variable across different field conditions and environmental contexts, significantly affecting the precision of estimated grazing times.

To address these limitations, the next steps will include:

- **Exploratory analysis** of the available raw data to characterize data gaps and positional errors;
- **Assessment of data quality impact** on grazing time predictions, identifying how missing or imprecise data affect model outputs;
- **Development of data correction methods**, including strategies for imputing missing values and adjusting inaccurate positions;
- **Refinement of prediction models** to improve their robustness and ensure reliable performance under diverse grazing conditions.

Once the prediction models demonstrate sufficient reliability and accuracy, the project will move toward designing value-added services for end users. These may include:

- **Interactive grazing maps** showing historical and real-time animal movement;
- **Heatmaps** to evaluate grazing pressure and optimize pasture management;
- **Automated grazing calendars** to assist in planning and traceability for farmers, dairies, and quality certification bodies such as PDO organizations.

3.4 Description of case study D: Integration of different technologies, including animal breeding

Aims and background

This Case Study will examine how digital technology can boost animal breeding. Livestock farming systems are expected to evolve in the future under the combined effects of climate change, society's view of livestock farming practices and the necessary transition to more sustainable, circular systems that are more closely integrated into agroecosystems. Animal populations will have to adapt to these changes, and breeding goals, which until now have been essentially based on improving economic efficiency, will also have to take account of environmental targets (at the least, reducing negative environmental impacts) and societal objectives (taking greater account of one-health and one-welfare targets).

Large numbers of data have long been used to predict the breeding values (EBVs) of animals. Breeding values are used to select future breeding stock. In dairy cattle, for example, phenotypes (lactation data, reproduction data, etc.) from several millions of animals are used every year for this purpose. Complex genetic information systems have been set up to collect, centralise and manage the data in a standardised way, then compute the EBVs and distribute them back to breeders. A typical genetic information system for ruminant species is shown in Figure 12. The situation is simpler for monogastric species, where selection is most often carried out on a small number of farms (nucleus herds) with, in many cases, breeding companies combining several roles.

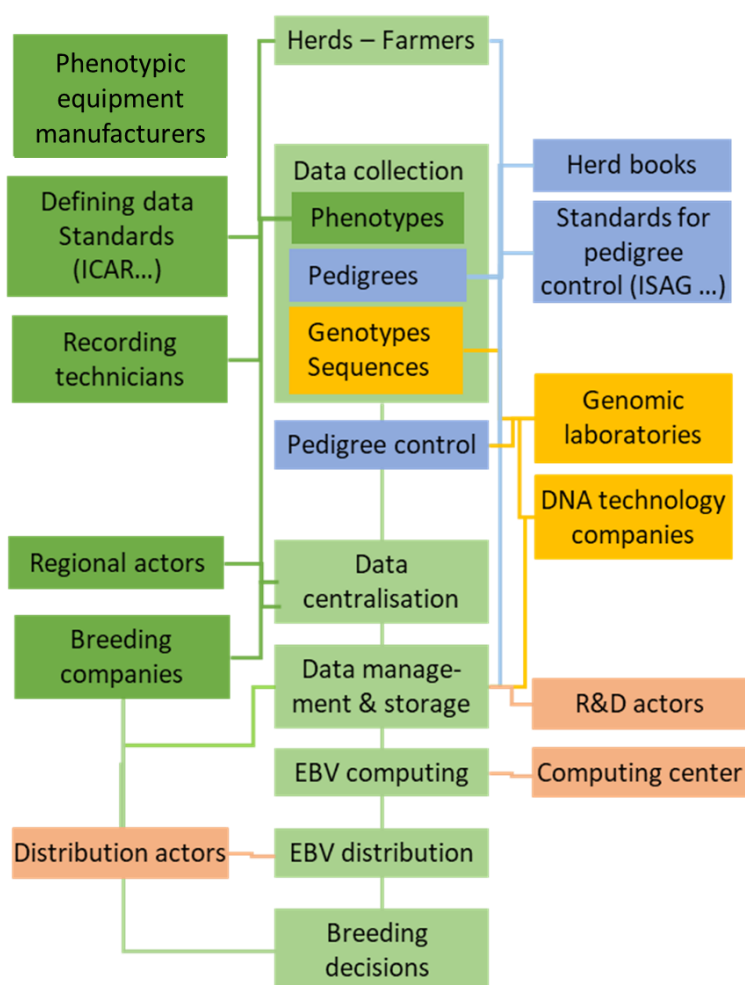


Figure 12. Schematic representation of stakeholders involved in data exchange and use in a typical breeding programme.

D3.2 Case studies follow-up report

Increasing use of digital tools in recent years has already changed several aspects within standard organisations working in the field of animal breeding. In particular, the increasing value of data and changes in data regulations have led to a more precise definition of data ownership (breeders are still the main owners of data) and to the implementation of tools allowing breeders' consent for breeding use to be obtained easily. Increasing volume of data collected on farms, mainly for non-genetic purposes (precision farming, welfare indicators, information collected on monogastric production farms), offers new opportunities for integrating new traits into breeding programs. However, because these data are not collected for breeding purposes, their repurposed use may not be straightforward and the possibilities and benefits of using them in animal breeding programs need to be investigated. This challenge will be in the focus of case study D.

Materials and methods

Case study D has been organized into three sub-actions:

- S1. Improve knowledge and understanding of the positions of animal breeding actors and stakeholders regarding data and digital technologies;
- S2. Identify new traits and data sources likely to be used in the future, either to predict breeding values or to monitor the consequences of selection;
- S3. To understand and find solutions to the problems brought by the new data (data heterogeneity, high-throughput data (HT data)), with a first focus on HT data.

S1: Animal breeders' and stakeholders' positions regarding digital technologies

This section uses a methodological approach combining literature analysis and qualitative interviews, with a view to designing a quantitative survey to be carried out on a larger scale in Europe. A literature review (scientific publications, technical reports and policy documents) is currently underway to explore:

- The breeding industry visions of the future of livestock production and farming systems; in view of these visions, how are breeding objectives and criteria shaping up?
- The most interesting current and future technologies for breeding purposes;
- The potential use of data collected for other purposes (precision livestock farming, health management, welfare assessment, etc.) for breeding;
- The interest of digital technologies to offer solutions to obtain new phenotypes and collect new information for breeding?
- Critical challenges, opportunities and potential obstacles to their widespread use in animal breeding?

The literature review has already provided a scientific and technological basis for identifying priority areas for development, comparing the technological maturity of different sectors and gaining insight into the different concepts and modalities of data governance and management tools. It also provided the basis for the preparation of interviews with French key actors and stakeholders in animal breeding. While not necessarily representative of the European industry as a whole, the relevance and diversity of the subjects covered enabled us to consider that an adequate amount of material on which to build the questionnaire for Europe-wide actors and stakeholders was obtained. About 15 interviews were conducted, covering the main livestock sectors (cattle, sheep, goats, pigs and poultry), as well as the main activities: genetic data management centres, genetic evaluation agencies, breeding divisions of technical institutes, breeding companies (ruminants, pigs, poultry), and representatives of national agricultural authorities. The interviews explored different aspects such as:

- The current use and impact of digital technologies.
- Perceptions of digitalisation (value, risks and constraints).
- Existing and anticipated data flows.
- Legal and ethical aspects of data use.
- Needs for training, infrastructure, and support.

D3.2 Case studies follow-up report

A large-scale questionnaire is being finalized. Its development has required additional time, especially because of the will to use interviews for its development. The survey will be sent out to potential respondents during the summer 2025. It will provide a quantified view of the level of adoption of digital technologies, assessing the digital maturity of each sector, obtaining information on perceived facilitators and obstacles, on the impact of regulations, and identifying differences between countries or regions.

S2: New traits and data sources

This sub-action aims to identify, through the literature review or from interviews and the questionnaire, new traits that could be considered in breeding schemes, along with a multi-criteria evaluation of the different approaches used or under development to phenotype these traits. We are primarily targeting three groups of traits: i) behaviour, health, and welfare; ii) environmental impacts; and iii) feed resource use, although other relevant traits may also be considered.

The multi-criteria evaluation includes traditional criteria such as measurement accuracy, but also aims to assess the maturity level of the technology for animal genetics purposes—particularly the ease of large-scale implementation (cost, user-friendliness, existence of ontologies, reference/standard measurements, or methods allowing for standardization or joint use of similar measurements).

Another issue addressed is data interoperability. This is a critical concern for the vast majority of data that are collected and managed either at the farm level or across groups of farmers and phenotyping tool manufacturers. Based on a situation assessment for a few target traits i) methane production measurement; ii) a behavioural measurement (currently leaning toward social behaviour); and iii) a health indicator to be defined in the previous item (such as vaccine response). The objective is to identify the various barriers that hinder their use for animal genetics purposes.

S3: High-throughput data issues

This sub-action examines how to manage and utilize large volumes of heterogeneous data, which are increasingly generated through digital technologies in livestock breeding. This is related to two aspects that are summarised below.

Data quality and filtering. One of the main challenges is to ensure the accuracy and usability of high-volume data. To address this, we investigate the application of advanced filtering and processing tools. A practical case is the Walk-over-Weighing (WoW) system developed and tested by INRAE. This system enables:

- Continuous liveweight monitoring of individual animals;
- Low-stress, autonomous data collection in extensive systems;
- Real-time identification of anomalies (e.g., health issues, reproductive events).

To manage the variability and outliers typical in field conditions, the Kfino algorithm, a robust Kalman filter, has been developed and integrated into the ORIOLE web application, which enables data cleaning and visualization. A mobile application is also being developed to improve on-farm usability.

Broader high-throughput data issues. Beyond WoW, the case study is evaluating other sources of high-throughput data, such as:

- Genomic sequencing and SNP genotyping data;
- Behavioural data from accelerometers and cameras;
- Environmental data (e.g., temperature, humidity, microbiomes).

Interviewed stakeholders highlighted the following challenges:

- Data heterogeneity across sources and formats;
- Need for real-time or near-real-time analytics;
- Cost of infrastructure and data storage;
- Staff training and turnover affecting long-term data handling.

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Efforts are made to develop interoperable data infrastructures and support tools to manage the scale, complexity, and variety of these data streams.

First results

The first 18 months of this case study have resulted in several important outcomes. These can be summarized as follows:

- Interviews have confirmed the high strategic interest in digitalization among actors and stakeholders, with widespread recognition of its potential to improve genetic evaluation and overall breeding efficiency. Yet, the challenges are numerous, and practices need to evolve to successfully make use of digitalization.
- The literature review and interview synthesis have exposed clear gaps in trait definitions, legal frameworks, and technical standards.
- There is broad support for developing new traits, but a clear demand for better guidance and harmonization efforts at the European level.
- The WoW platform demonstrated the feasibility of field-level automatic phenotyping, and its associated tools (Kfino, ORIOLE) offer a model for handling other high-throughput data sources.

Discussion and future plans

The next steps for CS-D include: i) Preparing and distributing the European-wide stakeholder survey; ii) Finalizing the literature review and publishing the results; iii) Organizing a stakeholder workshop on new trait development (sub-action 2), and iv) Investigating links with other case studies, e.g. CS-A, CS-B and CS-F.

3.5 Description of case study E: Data digitalization for environmental impact assessments using LCA

Aims and background

Environmental impact assessments of livestock production systems using LCA face many challenges, including the time and resources necessary for conducting LCA and the high variability in the quality of the estimated environmental performance indicators for the livestock farming systems because of, for example, the variable quality of farm-level LCA data (e.g. incomplete data on feed type, composition, supply and consumption, regarding fuel and electricity consumption, difficulty to access livestock farming management data in general, absence of country-specific or case-specific methods for emission estimation from livestock farms etc.). Case study E (CS-E) aims to partially address these challenges by organizing and facilitating farm-level data collection in intensive pig and poultry farming systems and increasing the speed of conducting LCA studies for such systems, through i) the development of user-friendly web-based farm-level primary data import templates for running LCA and ii) the development of a prototype software that uses the imported primary data to derive farm-level life cycle inventory datasets which would facilitate the estimation of the environmental performance for products of intensive pig and poultry farms, in compliance with the EU-PEF (Product Environmental Footprint) method.

The tools that will be developed are expected to directly benefit stakeholders of agri-food supply chain systems related to LCA practitioners, for example, consultants, research and academic institutions, feed and food (meat) industry and pig and poultry farmers and farmers' cooperatives. Besides already reported stakeholders such as governmental and regulatory bodies, technology providers, software developers and logistics operators, indirect benefit from the use of these tools is expected for all stakeholders which are interested in knowing the environmental performance of pig and poultry product supply systems.

Materials and methods

This deliverable focuses on the progress regarding the development of the first of the two interconnected LCA tools, i.e. the user-friendly web-based farm-level primary data import templates for running LCA. This development includes the finalization of the farm-level primary data import templates, after having i) refined the data requirements for farrow-to-finish pig systems (focusing on the nursery, growing and finishing stages of pigs) and for broiler systems (starting, growing and finishing stages), ii) built these templates in MS-Excel format and iii) established a web-based architecture based on the templates in MS-Excel format.

Refinement of data needs

The refinement of the primary data needs was completed considering that the farm-level LCA datasets (i.e. the output of the second LCA tool, prototype software that uses the imported primary data to derive farm-level life cycle inventory datasets) should include the product outputs, inputs from nature, material inputs (e.g. feed and bedding materials, fuels), energy inputs (e.g. electricity), and emission (air, water and soil) and solid waste outputs on an annual scale for the farms that use these tools.

Excel-based data collection templates

The Excel-based data collection templates were systematically developed to enable comprehensive, consistent, and user-friendly recording of key inventory data at the individual farm level. The templates aim to generate high-resolution datasets essential for conducting LCAs that capture system-specific variability and enable reliable estimations of environmental burdens. The templates are designed to:

- **Quantify annual product outflows** such as live animal sales, meat yields, and manure exports;
- **Characterize inputs from nature**, including water, feed crops, and land use;
- **Capture material and energy inputs**, including purchased feed, bedding materials, fuels, and electricity.

The structure and the data categories within these templates are aligned with internationally recognized guidelines for gas emission estimation. Air emissions from manure management (mostly methane, nitrous oxide and ammonia), energy-related emissions (e.g. carbon dioxide from the combustion of fuel for heating of the animal housing installations) and to a lower extent air emissions from enteric fermentation (i.e. methane) will be estimated using the methodologies outlined in the latest IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019) and the EMEP/EEA Air Pollutant Emission Inventory Guidebook (EEA, 2023). Manure management, enteric fermentation, and energy-related emissions are covered through tiered methodologies (Tier 1 and Tier 2), with input fields facilitating the use of more accurate Tier 2 parameters where available.

In detail, the templates support transparent goal and scope definition, facilitate inventory data gathering for life cycle inventory (LCI) modelling, and are intended for use in comparative attributional LCAs. They enable **cradle-to-farm-gate system boundaries**, encompassing upstream and on-farm processes. The templates are structured to facilitate both **Tier 1** (default emission factors) and **Tier 2** (farm-specific parameters) estimation by collecting data on: i) Animal categories and weights, ii) Housing systems and manure storage, iii) Diet composition and feed intake and iv) Ambient temperature and retention times. To ensure representativeness and enable scenario analysis, input/output data are disaggregated by: i) Production stage: e.g., weaner, grower and finisher pigs and ii) resource type: material inputs, energy, water, land. The templates are methodologically mapped to include activity data modules (user input).

Web-based data collection templates – technology stack

To support and scale up the data collection process beyond Excel templates, a web-based platform was developed to allow farm operators and researchers to input their primary data directly through a secure, user-friendly interface.

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The frontend was built using Next.js 14, a modern React-based framework that uses the new App Router system to manage navigation and improve performance (Next.js, 2023). On the backend, the platform uses Supabase, an open-source backend-as-a-service built on PostgreSQL. Supabase was chosen for its ability to combine database management, user authentication, and API development in a single integrated environment (Supabase, n.d.-a).

For user access, the system uses email and password authentication through Supabase Auth. To ensure data security, Row-Level Security (RLS) is applied, meaning that users can only see and manage the data they've submitted themselves (Supabase, n.d.-b). This setup ensures both flexibility and data privacy, which are critical for handling potentially sensitive farm-level information.

Finally, the platform supports CSV exports, allowing users to download their data for use in external LCA tools or for integration into broader databases and reporting frameworks.

Web-based data collection templates – Application architecture

Authentication workflow: To protect data and ensure proper user access, the platform requires all users to sign up or log in before reaching any dashboard or data entry areas. Authentication is handled through Supabase Auth, which works in combination with the Next.js middleware system to securely manage login sessions. No part of the application is visible or usable without successful authentication. This ensures that all data remains private and that each user can only access their own information.

Application data flow: The logic of how users move through the platform is summarized in the Application Flow Diagram (Figure 13). Here's a brief overview of how it works:

- When a user sends a request, it first passes through a `middleware.ts` file that checks whether they're logged in.
- If authenticated, the platform renders the necessary pages using a mix of server-side and client-side components—making things faster and more responsive.
- Any data the user enters or requests is handled securely through Supabase API calls.
- Most importantly, Row-Level Security (RLS) is active in the database. This means users only see and interact with the data they've personally entered—no one else.

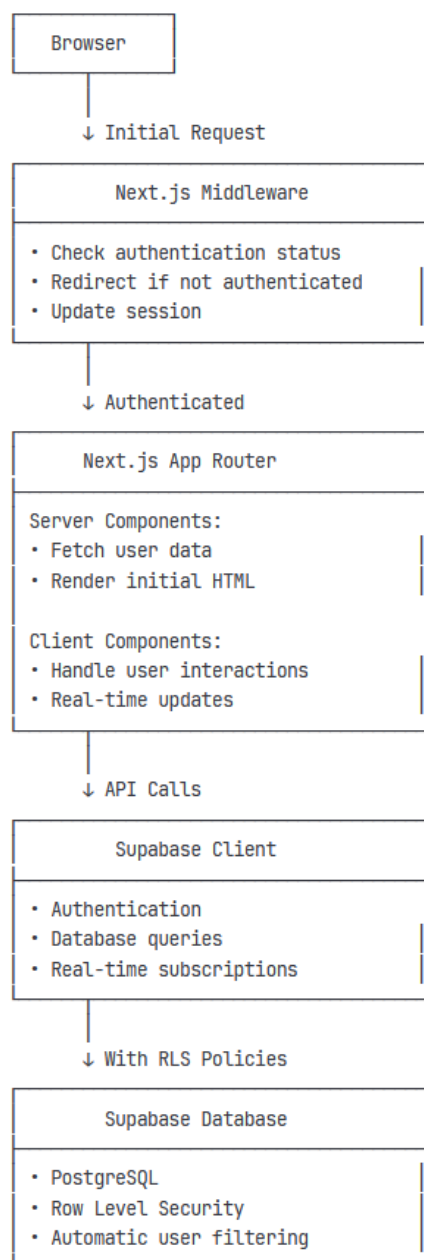


Figure 13. Application flow diagram for the web-based data collection templates.

Web-based data collection templates – Database Schema

The platform's database is structured (Figure 14) to support secure, user-specific data storage and access. It consists of three core tables:

- **auth.users:** This is the default table provided by Supabase to handle user authentication. It stores each user's unique ID and login credentials.
- **profiles:** This table adds some flexibility by storing additional user details, like name and email, which can be used to personalize the experience or manage access.
- **user_data:** This is the heart of the platform. It's where all farm-related entries are stored—such as livestock numbers, feed inputs, and energy use.

Every record in the user_data table is linked to the user who submitted it via a user_id. To make sure that data stays private, the system uses Row-Level Security (RLS). This means users can only see or change the records they created. In other words, all actions—whether it's adding, viewing, editing, or deleting data—are tightly controlled and limited to each user's own entries.

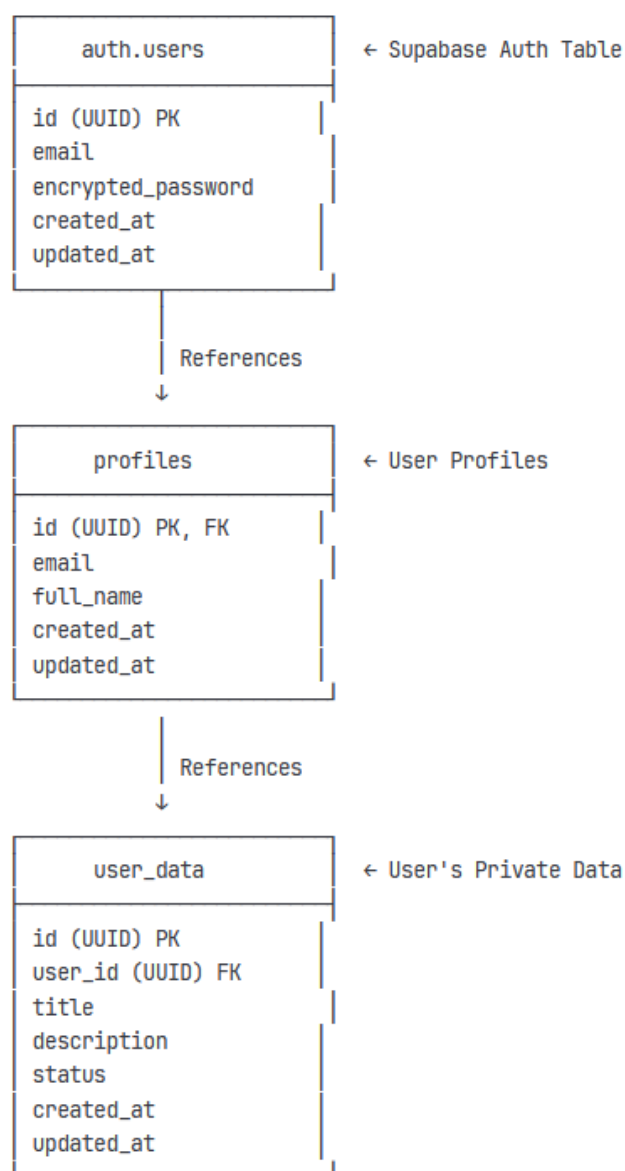


Figure 14. Database schema visualization (web-based data collection templates).

Web-based data collection templates – key components and file structure

The platform's source code is organized into modular components that collectively manage user authentication, data flow, and interface rendering. Below is a summary of the core implementation files and their roles within the system:

middleware.ts: This middleware intercepts every incoming request to the platform. It verifies whether the user is authenticated, manages session tokens, and automatically redirects unauthenticated users to the login page (/login).

lib/supabase/server.ts: This module sets up the Supabase client specifically for use in server-side components. It ensures secure handling of cookie-based sessions and manages persistent user sessions across requests.

lib/supabase/client.ts: This file initializes the Supabase client for use on the client side. It also supports real-time subscriptions, allowing the frontend to respond instantly to changes in the database without requiring manual refreshes.

app/dashboard/page.tsx: This is the main entry point for the user dashboard. It is responsible for rendering user-specific views and loading relevant data tied to the authenticated session.

types/database.types.ts: This TypeScript utility provides type-safe access to all Supabase data structures. It ensures that database queries and responses are consistent with the defined schema, helping prevent runtime errors and improving code reliability.

Web-based data collection templates – Data security and Row-Level access control

To protect user data and maintain strict access boundaries, the platform uses **Row-Level Security (RLS)**, a built-in feature of the Supabase database system (Figure 15). This mechanism ensures that each query made from the frontend is automatically filtered based on the authenticated user's session. As a result, users can only access, modify, or view the data they have personally entered.

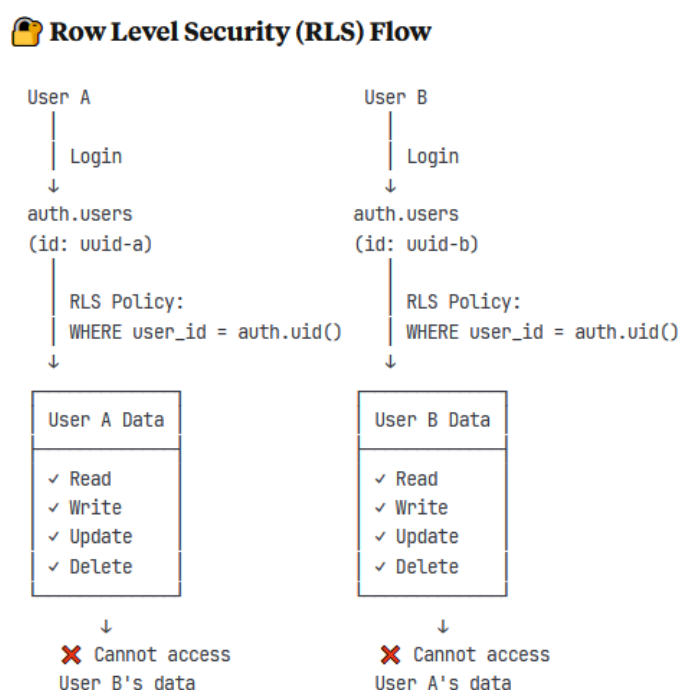


Figure 15. Row Level Security (RLS) flow (web-based data collection templates).

Importantly, this protection extends beyond the user interface. Even if a user attempts to interact directly with the API, RLS policies are enforced at the database level, preventing any unauthorized access to other users' records.

This setup provides a strong layer of security while also supporting compliance with data protection regulations such as the General Data Protection Regulation (GDPR). By embedding RLS directly into the platform's core data architecture, the system ensures that all user data remains isolated, secure, and properly managed.

First results

Status of Excel-based data collection templates

A first version of the MS Excel-based data collection templates has been finalised for both growing pigs and broiler production systems. Examples of the qualitative and quantitative information requested for the animal inventory in Figure 16.

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Dashboard access: Once logged in, users are directed to a personalized dashboard (Figure 17). This serves as the central navigation hub, providing access to introductory information about the project, usage instructions, and farm selection tools. Users are prompted to select the type of farm they operate (e.g., pig or poultry), which determines the structure of the input forms they will interact with.

Farm type selection and input modules: After selecting their farm type, users proceed to input data relevant to their production system (Figure 18). Input modules are organized by housing unit (e.g., grower house, finisher house) and are supported by contextual guidance and clear instructions. Each section helps ensure that data is entered consistently and accurately, with action buttons enabling intuitive navigation.

Interactive data tables: A key feature of the user interface is the use of dynamic, interactive tables for entering production data—such as animal outputs, feed composition, and material use (Figure 19). These tables allow users to add new rows for multiple entries, edit or delete data as needed and export their entries as CSV files for downstream analysis

The combination of structured navigation, tailored forms, and flexible data entry tools makes the interface both user-friendly and scientifically robust, supporting reliable data collection for farm-level life cycle assessment.

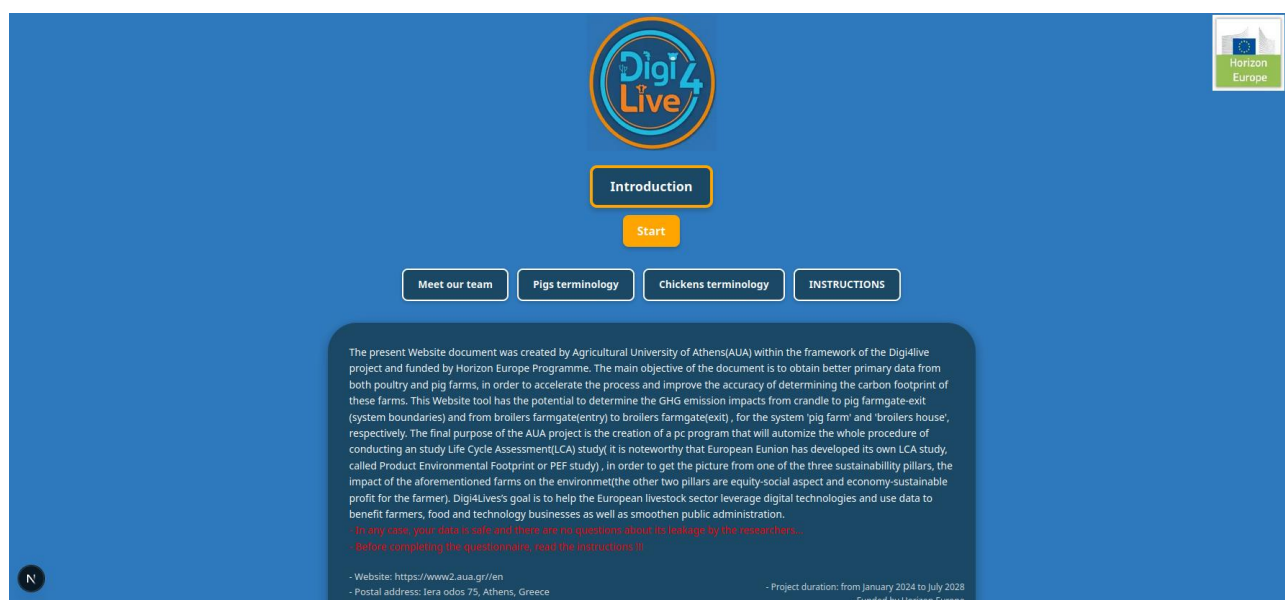
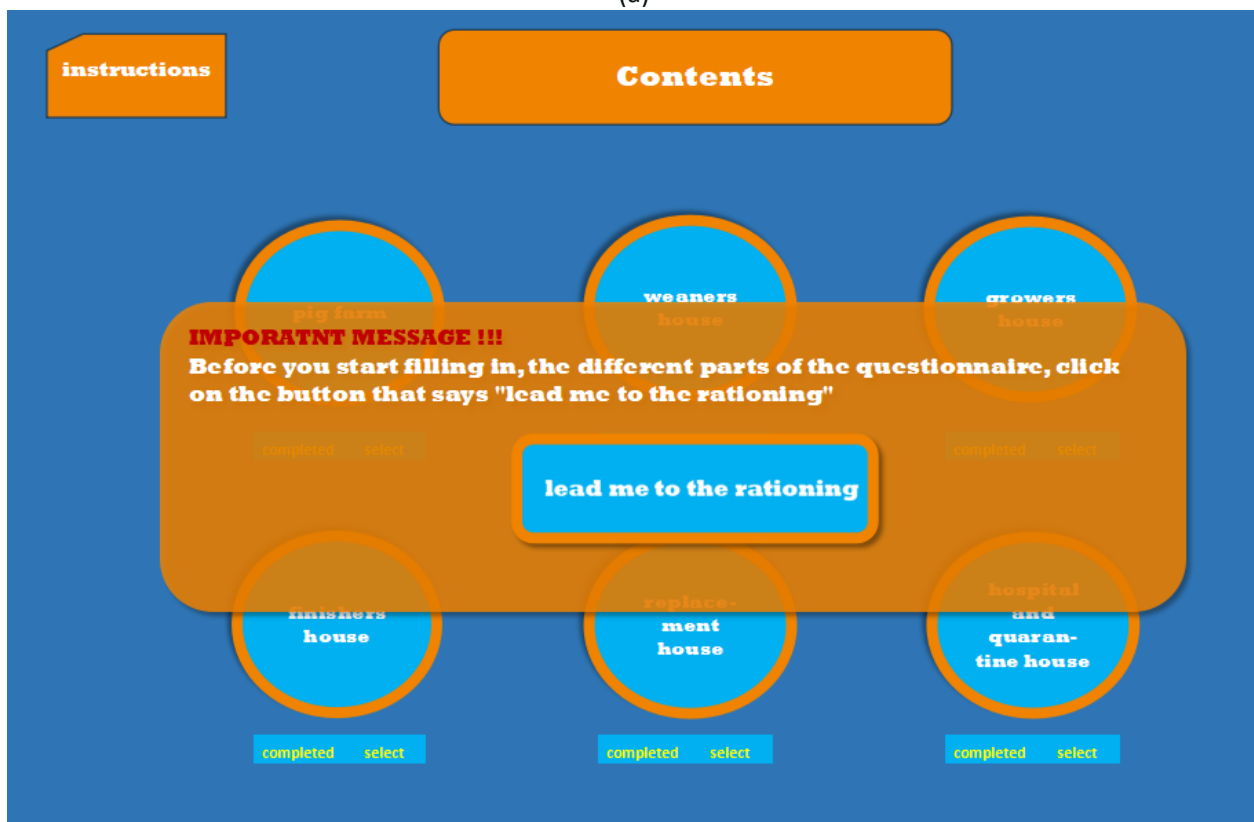


Figure 17. Personalized dashboard of the current version of the web-based data collection templates.



(a)



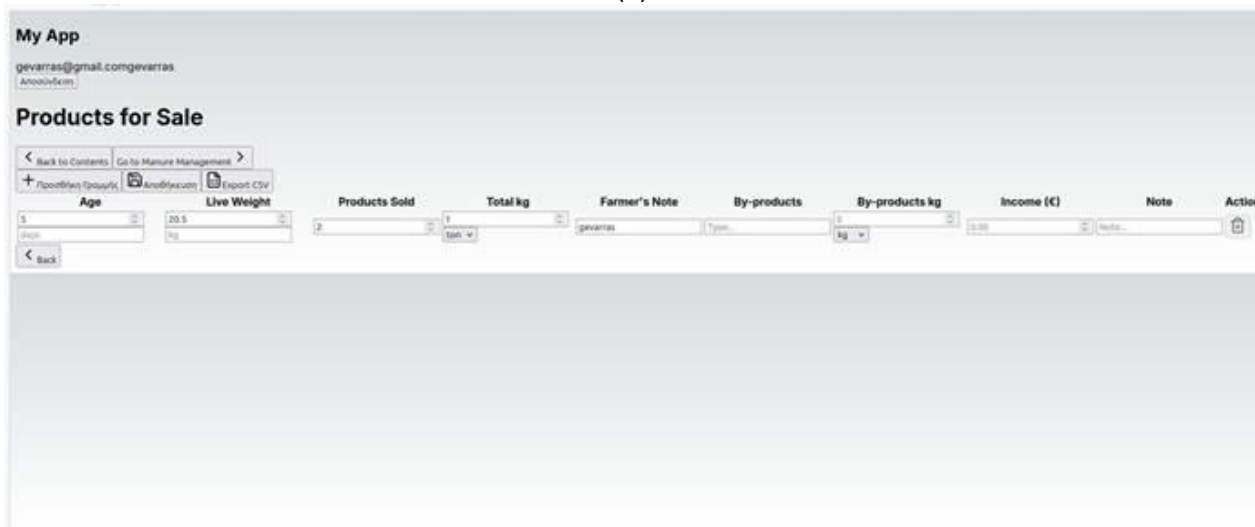
(b)

Figure 18. Selection of farm type (growing pigs or broilers) (a) and input data categories after selecting farm type (b).

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(a)



(b)

Figure 19. Interactive data tables for completing growing pigs' product outputs.

Discussion and future plans

Excel-based data collection templates

It was attempted that each sheet of the developed an Excel-based data collection templates is organized to mirror to the extent possible real-life farm operations for real-life farm operations (growing pigs and broiler production). The modular layout of the file supports flexibility for diverse farm configurations while maintaining compatibility with emissions estimation protocols. Preliminary testing by the developing team confirmed that the templates accommodate both Tier 1 and Tier 2 inventory requirements, offering a practical bridge between theoretical gas emission estimation and on-farm data availability. The resulting structure sets the stage for the web-based version of the same templates. As these Excel based templates are complete and translated to Greek, they allow provision of feedback to these data collection needs by local pig and poultry farmers. It was agreed that that specific meetings will be organised for discussion of data collection issues and training on the use of these data collection templates.

Web-based data collection templates

The architectural setup of the platform keeps it both secure and user-specific, while allowing flexibility for data entry and management from multiple farms. The database setup keeps things clean, secure, and scalable, making it easy to manage data from multiple farms without any risk of cross-access or data leakage. Together, the key components and the file structure of the platform's source code form the backbone of a secure, dynamic, and user-aware web application, tailored to collect and manage primary data for building farm-level LCA datasets.

While the platform is already operational, further enhancements are planned to expand functionality and improve user experience. These include:

- Improved input validation to reduce data entry errors
- Interface refinements to support smoother navigation and clearer instructions
- Role-based access control to accommodate different types of users (e.g., researchers, administrators)

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- Direct integration with emission estimation methodologies to enable real-time analysis and development of farm-level LCA datasets (connection to the second LCA tool, a more complete prototype software for LCA dataset development)
- Multilingual support to ensure accessibility across different regions

The beta version is being presented for demonstration and feedback purposes, in line with the project's objectives and timeline. Insights gathered during this phase will help guide the following updates and ensure that the system meets the practical needs of users.

3.6 Description of case study F: Policy monitoring, policy impact and administration

Aims and background

Monitoring agricultural and rural policies, including their impact and compliance on farms with the policy rules, requires plenty of resources both from the farmers and public administration. Most of the documentation is currently collected and stored in manual forms or several databases. Better flow of information and wider availability of outcome-based data from farms could enable more efficient and low-cost monitoring of farms' compliance with policy rules and assessment of policy impact. Efficient management of data could also reduce the administrative burden on farms and affiliated industries handling live animals and animal products, as well as on the competent authorities. The public sector could use the stored data to effectively monitor the implementation of common agricultural policy. Finally, the private sector could utilise the data for product labelling.

The European Union aims to establish common sectorial data spaces to make data across the EU available for access and reuse (European Commission, 2025). The livestock sector is envisioned to become part of The Common European Agricultural Data Space (CEADS). Both the technological and governance building blocks for data spaces are still under active development. This case study aims to study and demonstrate the value of combining different data sources from farms in a fair and trusted manner. As part of the work, an open source proof of concept data space and data models for the cattle sector are developed.

The goal of this case study is to develop dataspace proof-of-concept which will be apply to e.g., policy monitoring, environmental certification and food traceability through the development of a Digital Product Passport (DPP) for cattle to increase transparency, accountability, and traceability for each actor in the value chain. The cases will be developed at a Member State level, and thereafter upscaling potential at the EU level will be explored.

Materials and methods

In this case study we will develop a data-sharing strategy using data spaces involving farmers, processors, technology suppliers and authorities and showcase it in the context of an EU member state. In the first 12 months of the Digi4Live project the scope of the case study has been defined in collaboration with project participants and the stakeholder interviews. Relevant digital data sources available from Finland have been studied and the data needs for policy monitoring and administration were mapped. For policy monitoring, the key reviewed documents were the national greenhouse gas inventory report (Statistic Finland 2024), Finland's Cap Strategic Plan (MMM, 2022) and Finnish Food Authority's instructions for farmers record-keeping for 2024 (Finnish Food Authority 2024).

The case study will explore data exchange between public and private parties in the dairy sector with 2 use cases using data space technologies. Use case 1 will focus on administration and address a better exploitation of the Finnish Cattle registry; while use case 2 will focus on policy monitoring and the possibility of using digital data sources and data spaces for the national greenhouse gas inventory reporting. Wider policy needs

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and implementation opportunities will be explored by engaging and consulting competent authorities across Member States and the European Union. This will be done through online workshops and an EU-wide survey.

In use case 1 reporting system based on the Finnish Cattle Register data will be created. Detailed requirements for the identification and registration of cattle are laid down in a Commission Delegated Regulation 2019/2035 and Commission Implementing Regulation (EU) 2021/520. The new Finnish National Act on the Identification and Registration of Animals (1069/2021) entered into force on 1 January 2022. The Decree of the Ministry of Agriculture and Forestry (67/2022) on the identification and registration of animals issued under the Act entered into force on 24 January 2022. Currently, data of animal establishments is available only at the establishment level. This work aims to connect establishment data with animal data so that geographically real-time data of kept bovine animals would also be available. Instruments to observe the movement of animals and causes of removal will aid in official control planning of both animal welfare and animal health and risk preparedness.

Among others, the following information will be extracted from the cattle register data:

- The numbers of farms and animals,
- Farm production types, categorization of farms by production types,
- Size of farms, categorization of farms by size,
- Categorization by (wanted) geographical regions,
- Transportations of animals: how many animals per given time are arriving/leaving,
- Mortality rate per farm and per age categories, and the cause of removal.

In use case 2, the digital data sources available from Finnish dairy farms will be assessed for availability, interoperability and suitability for use in GHG inventory. Currently, large parts of the agricultural inventory are based on Tier 2 methods, which do not capture the introduction of new emission reduction technologies or management changes at the farm level due to a lack of activity data. The information already collected at the farms has a great potential for increasing the accuracy of the inventory if it can be made available and verified for reporting purposes. The dual use of the data for LCA will be explored to avoid the dual entry of data from the farmers' side and to increase the reliability of data.

Technical solution

The technical solution for data sharing will be with the IDSA (International Data Spaces Association) reference architecture model (IDS-RAM, IDSA 2022) which is currently under standardisation. The case study will deliver an open-source software solution for setting up an IDSA compliant minimum viable dataspace (MVDS) based on an open-source IDSA connector. The data producer will demonstrate the use of milking robot data from Luke research farms, using the ICAR Animal Data Exchange standard and the data consumer will access the data that is relevant for the digital product passport according to the initial plan below. The MVDS concept is defined in the IDS-RAM as having at least two ID connectors, a certificate authority and a dynamic access provisioning service. These building blocks will allow us to explore and demonstrate the technical capabilities of the dataspace related, e.g. to access management, technical requirements for the data sharing service and throughout the service. MVDS can easily be extended to include additional data sources, data producers and data consumers by implementing additional connectors. The use of Gaia-X standard for decentralised user identification will also be explored. The use compliant commercial data space technologies will be explored in collaboration with stakeholders between months 18 and 36 of the project.

First results

Use case 1

First version of the reporting tool has been developed at FFA (Figure 20). The following information, can now be extracted from the cattle register data:

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- Number of farms and animals – categorized by farm production types
- Categorization of animals by age groups
- Mortality rates

Various definitions for farm and animal groups are needed for multiple reporting/compilation needs. The reporting tool can be modified to fulfil the varying definitions.

Figure 20. Example of the output of reporting tool. The chosen definition can be built on the menus on the left. The output includes number of farms and number of animals in the chosen category/definition. The reporting tool operates currently only in Finnish.

The farm level data of the selection (identification of the farm and detailed information on farm's animal population) are visible in the reporting tool but are not shown here due to data protection reasons.

Use case 2

Digital data sources available from Finnish dairy farms have been evaluated for their availability, interoperability, and suitability for use in GHG inventory. The data sources relevant to use case 2 are briefly described in Table 3.

Table 3. On-farm data sources for Tier 3 GHG inventory.

Type of data	Description
Milking robot	Milking robot systems collect on-farm data related to milking visits and animal movements. They record milk quantity and quality, animal body condition scores, and concentration intake, which can be used for cow-level GHG calculations. Data exchange is facilitated through a universal interface developed by the International Dairy Data Exchange Network (iDDEN), based on the ICAR Animal Data Exchange standard.
Concentrate feeder	Automated concentrate feeders track feed availability and/or intake at the individual animal level. These records can serve as input for cow-level GHG calculations. However, data access interfaces are specific to each manufacturer.
Feeding wagon, feeding robot	Feeding wagons record feed composition data, while feeding robots track feed availability for animal groups or the entire herd. As with concentrate feeders, data access interfaces vary by manufacturer, and not all provide them.
Field production records	Detailed data about field activity is recorded in different farm management information software. In Finland at least the dates of farming operations, the used inputs and harvested yields are being recorded. The yield data is mostly based on farmer estimated. The data has potential to be used for farm specific LCA and if made more widely available to also be in used in national GHG inventory-

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These on-farm systems typically store milking, feeding, and management data only temporarily, as they are not designed for long-term storage. To ensure data availability throughout and beyond a cow's lifetime, we propose establishing a centralized database to store relevant data extracted from on-farm systems. This would ensure accessibility for the Digital Product Passport (DPP) server.

The initial version of the Digital Product Passport for cattle, which uses near real-time data, has been designed to support not only Tier 3 GHG inventory but also other practical applications such as product life cycle assessments and regulatory monitoring (Figure 21). Key data sources identified for the DPP include the bovine registry, herd monitoring and management system, milking robot system, farming management system, veterinary database registry, and farm audit companies. As part of the use case 2, we are currently implementing mock-ups for a subset of these data sources. So far, we have demonstrated the integration of milking robot data, and future iterations will include data from the bovine registry and, if feasible, feeding data. This phased approach allows us to validate the technical framework and data interoperability before scaling to a broader set of sources. To calculate the carbon footprint, a dynamic LCA model such as Hietala et al. (2021) could be used, complemented with methods applied in Finland's National Inventory Report. We will investigate how to implement a Bovine DPP by exchanging the required data in the data space.

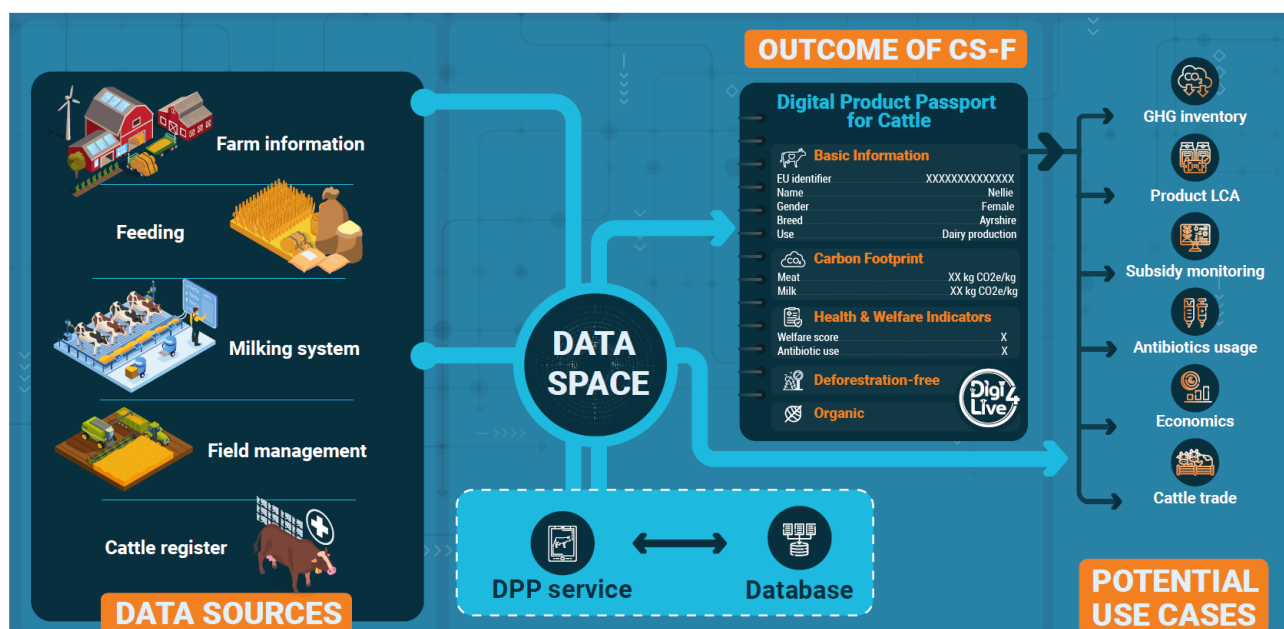


Figure 21. Concept of a Digital Product Passport for Cattle.

The technical implementation of the cattle DPP is based on the digital twin concept, already used in other industries such as the automotive industry's data space Catena-X DPP solution (Catena-X, 2024). The bovine digital twin is represented by an Asset Administration Shell (AAS), a core component of Industry 4.0 as defined by the Industrial Digital Twin Association (IDTA). The AAS serves as a digital representation of a physical or logical asset, in this case, a cow. It can be thought of as a digital envelope that contains all relevant information about the asset in a machine-readable and standardized format.

The AAS is divided into multiple submodels, each describing a specific aspect of the asset. These submodels are modular and extensible, allowing different stakeholders to access and contribute data in a consistent way. In the context of use case 2, the bovine digital twin is implemented as an AAS, with each cow represented by its own AAS instance. So far, we have defined four initial submodels for

- Basic information of an animal
- Milking sessions
- Milk analyses
- Greenhouse gas emission data

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Each submodel is described using a semantic Aspect Model (Figure 22), based on the open Semantic Aspect Meta Model¹ (SAMM) standard. The corresponding submodel template is generated from this description. AAS and submodel instances for each cow are managed and accessed via Eclipse BaSyx² server components, which provide a standardized HTTP/REST interface. This structure enables integration of data from various sources, supports animal-level GHG calculations, and facilitates the provision of aggregated data to the Digital Product Passport for cattle.

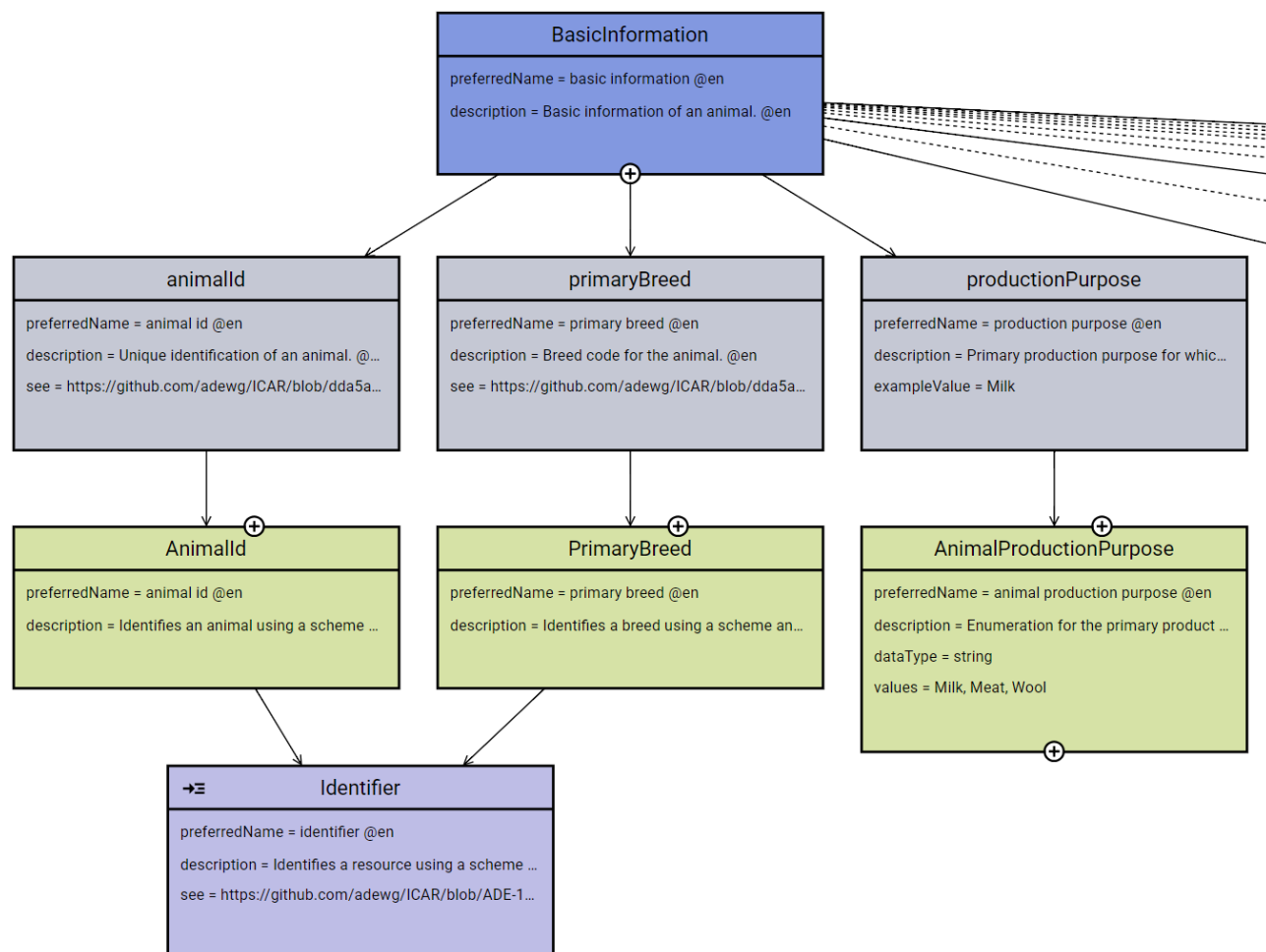


Figure 22. Example of the BasicInformation Aspect Model template. This aspect includes properties such as animalId, primaryBreed, and productionPurpose, with their content and data types defined in the model.

To demonstrate the use of milking robot data within the data space, we have developed the first data producer. This component is implemented as an OpenAPI Backend Express server³, which provides milking visit data from Luke research farms in the ICAR Animal Data Exchange JSON Standard format⁴. The ADE standard, specified by the International Committee for Animal Recording (ICAR), defines a common data model and exchange format for livestock-related data, including milking, feeding, health, and reproduction. It enables consistent and interoperable data sharing between different systems and stakeholders in the dairy sector.

Our adoption of the ADE standard is further supported by its uptake in the industry: it has been adopted by major data exchange networks such as the International dairy data exchange network (iDDEN) and JoinData, which facilitate data sharing between dairy farms, equipment manufacturers, and service providers. By

¹ Eclipse Semantic Modeling Framework in <https://eclipse-esmf.github.io/samm-specification/snapshot/>.

² <https://eclipse.dev/basyx/>

³ OpenAPI Backend package in <https://www.npmjs.com/package/openapi-backend>.

⁴ ICAR ADE standard in <https://github.com/adewg/ICAR>.

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aligning with this widely accepted standard, we ensure compatibility with existing data ecosystems and promote broader interoperability across the livestock sector.

Discussion and future plans

The development of the Digital Product Passport (DPP) for cattle within the Digi4Live project aims to demonstrate the potential of leveraging near real-time farm data for advanced environmental and regulatory applications. By integrating data from milking robots and designing a modular digital twin architecture using Asset Administration Shells (AAS), we have laid the groundwork for a scalable and interoperable solution.

A key insight from the initial implementation is the importance of data accessibility and interoperability across diverse on-farm systems. While the ICAR Animal Data Exchange standard provides a solid foundation for milking data, other data sources – such as feed intake and veterinary records – present challenges due to manufacturer-specific interfaces and limited standardization. We address this limitation by developing semantic aspect metamodels which provide a strictly defined API which can be used to develop e.g. emission calculation services operating in a data space. These metamodels will be further refined in the project and will be published openly during the project.

To case study used proof-of-concept approach and provides open source implementations of the developed components. The first data producer, based on milking robot data, has already been developed and is openly available⁵ and minimum viable data space based on IDSA components has been setup. Future development will focus on incorporating additional data sources, including the bovine registry and feeding data and feed production data, to increase the accuracy of the digital twin and support more comprehensive GHG inventory calculations and LCA calculation. The environmental footprint and the estimated operating costs of the DPP and data space components will be estimated based on simulations.

In the next phases of the project, we plan to:

- Complete the consultation of stakeholders through online workshop and survey.
- Connect the different data sources and a calculation service using minimum viable data space
- Expand the number of implemented sub model templates to cover a broader range of animal- or farm-level data in the digital twin.
- Develop additional data producers from and connectors for integrating feeding data.
- Demonstrate animal-level GHG calculation within the bovine digital twin.
- Collaborate with stakeholders to refine use cases and ensure alignment with regulatory and industry needs.
- Evaluate the scalability and performance of the DPP architecture.

⁵ <https://github.com/EU-Digi4Live/Mock-ADE-Server>

4. Discussion and conclusions

The Digi4Live case studies develop a broad set of digitalization concepts that seek to promote best digital practices in the livestock sector. Each of the concepts has been designed to have potential for EU wide upscaling and the economic and environmental performance of each concepts will be analysed using data collected during the project. The barriers and opportunities of each solution will be identified and the compliance with EU's new data and AI regulation will be ensured. In part the case studies and the Digi4Live project aim to ensure that livestock production is a part of Europe's "Digital Decade" transformation (EU Commission, 2020), using the potential of new technologies to achieve sustainability targets and remains a viable profession for new generations of farmers.

Each of the case studies has proceeded according to the plan and will expand the activities during the next 18 months. In addition to this deliverable, recorded presentations of each case study are available at the Digi4Live YouTube channel:

- Digi4Live Webinar #2: Harnessing Digital Tools for Animal Welfare, Breeding and Traceability. <https://youtu.be/qurwYcMXysE?si=nqFO2w4Bq4JArfqY>
- Digi4Live Webinar #3: Harnessing AI & Data Spaces for Animal Tracking, Sustainability and Governance. https://youtu.be/EQ8OLU_8unI?si=s_aN3USNWpoX2Rvi

The case studies actively seek collaboration with new stakeholders and their results and progress are widely disseminated through public webinars and through attendance in large scientific and industry and farmer events.

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