Synthesis report on Environmental, Economic, and Social C&B of farm digitalisation, draft M46

31 JULY 2026

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DOI: 10.5281/zenodo.21649824

Status: submitted draft not yet approved by the EC

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SYNTHESIS REPORT ON ENVIRONMENTAL, ECONOMIC, AND SOCIAL C&B OF FARM DIGITALISATION, DRAFT M46

Project name	**Maximising the CO-benefits of agricultural Digitalisation through conducive digital ECoSystems**
Project acronym	CODECS
Horizon Europe Topic ID	HORIZON-CL6-2021-GOVERNANCE-01-22
Project ID	101060179
Website	https://www.horizoncodecs.eu/
Document Type	Deliverable
File Name	D4-3_C&B_Farm_digitalisation_DraftM46_31072026.doc
Status	Final
Dissemination level	Public
Date of creation	28.07.2026
Keywords	Digital agriculture, Farm digitalisation, Environmental, Economic, Social-human, Costs and Benefits, Impacts, Perceptions
Authors	A. Gobrecht, M. Florez, V. Bellon-Maurel, (INRAE), C. Ilioupoulos, I. Theodorakopoulou, A. Sintori, T. Giotis (ELGO-DIMITRA), B. Herrera (UNI HOHENHEIM), L. Townsend, N. Mahon, T. Pittaway (HUTTON), M. Usca, E. Killis (BSC), K. Gauche (Institut Agro), D. Vergamini, T. Nadalutti, L. Ortolani, F. Lepore, G. Brunori (UNIPI), F. Bartolini (UNIFE)
Reviewers	Gianluca Brunori, Tiziana Nadalutti (UNIPI)
Version n.	1.0
Following updates	DEL4.4_C&B_Farm_digitalisation_FinalM48(M48)
Work package	WP4 - Costs and benefits analysis – Assessment of the potential of digital technologies in agriculture
Task number and title	T4.1 – Guidelines for data collection and reporting, T4.2 – Perceptions of C&B of farm digitalisation, T4.3 – Analysis of Environmental costs of the use of digital technologies at farm level, T4.4 – Analysis of Economic costs and benefits, T4.5 – Analysis of Social costs and benefits T4.6 Multicriteria Assessment
Work Package Leader	INRAE
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History of changes			
Version	**Date**	**Changes**	**Authors(s)**
0.1	02.06.2026	First draft	Alexia Gobrecht (INRAE)
0.2	15.07.2026	Second draft	Task Leaders
0.3	23.07.2026	Final Document review	Alexia Gobrecht (INRAE)
1.0	31.07.2026	First version approved and released	Gianluca Brunori, Tiziana Nadalutti (UNIPI)

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Executive summary

This deliverable synthetises progress made in WP4 of the CODECS project during the **first 46 months**. It focuses on the Costs and benefits analysis (C&B) of farm digitalisation across economic, environmental and social dimensions.

Three objectives guide this work: (i) capturing stakeholders' perceptions of digitalisation (T4.2), (ii) assessing C&B through dedicated methodologies for each sustainability dimension: environmental (T4.3), economic (T4.4) and social (T4.5), and (iii) preparing a multicriteria framework to explore trade-offs and synergies (T4.6).

Since the previous draft (D4.2, delivered M36), each task has moved from methodology and early results towards consolidated findings. Perceptions analysis (T4.2) has completed a second round of focus groups across the Living Labs, allowing stakeholder views to be examined not only as initial expectations but as they evolved once technologies were tested and experienced in practice; perceptions became more concrete and increasingly conditional on governance, support and trust rather than moving simply toward optimism or scepticism. The environmental assessment (T4.3) has completed comparative Life Cycle Assessments on ten use-cases, showing that digitalisation reduces overall environmental impacts in the large majority of cases, although about half of these reductions are modest, and some technologies increase specific impact categories tied to their own hardware life cycle. The economic analysis (T4.4) now covers thirteen Living Labs with farm-level data, nine of them analysed in depth: digital technologies proved economically viable in all nine in-depth cases under the conditions studied, with labour and input savings as the main drivers and farm size as the decisive factor for viability. The social/human-centred analysis (T4.5) is now complete and has been published in the Journal of Rural Studies (Florez et al., 2026); it confirms that digitalisation produces simultaneous and interdependent social costs and benefits across farmer well-being, work organisation and social interaction, rather than a uniform positive or negative effect. The multicriteria assessment (T4.6) has moved from conceptual design to an operational framework, tested through a pilot workshop with all 18 Living Lab coordinators in Ljubljana, generating a first exploratory dataset on trade-offs and enabling conditions.

Across all tasks, methodologies have been adapted to the diversity of the Living Labs, with guidelines and training provided to coordinators, and results have been systematically returned to Living Lab stakeholders through individual reports and demonstration events, so that farmers, advisors and local actors benefit directly from the knowledge generated.

This report remains an incremental draft. Several analyses are still being finalised – notably the comparative interpretation of the second-round focus groups (T4.2), the qualitative environmental analysis for Living Labs where LCA was not feasible (T4.3), and the completion of scoring and cross-case comparison in the multicriteria assessment (T4.6). Individual LL reports related to the studies conducted in each task are available in the ZENODO project repository and the final, fully consolidated synthesis report, integrating economic, environmental and social findings into a single cross-dimensional analysis of trade-offs and synergies, will be delivered at M48.

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1 Introduction

1.1 Objectives of WP4

WP4 is mainly focused on CODECS Specific Objective 4 "**Providing data on the costs and benefits of digitalisation in a variety of European farming contexts, by setting up and carrying out user-friendly assessment methodologies**".

It also contributes to objective SO6 by "**feeding public policy recommendations with evidences"** and to SO7, by "**providing assessment tools and feeding the platform with examples in order to raise awareness"**. For doing so, the WP has been divided into 6 different tasks:

- to capture stakeholders' perception of various costs and benefits along the 3 axes of sustainability (T4.2),
- to assess the environmental, economic and social impacts of digital technologies in a participatory way (T4.3, T4.4 and T4.5),
- to facilitate a conversation on trade-offs and synergies between costs and benefits (WP4.6).

Methodologies have been set up or adapted to be applied in the LL, which was carried out in T4.1 (guidelines). For sake of clarity, guidelines will be presented within each task, separately, in order to be associated with results, when available.

For more details on the methodologies and data collection protocols, refer to the previous versions of the deliverables:

- DEL4.1_C&B_Farm_digitalisation_DraftM24
- DEL4.2_C&B_Farm_digitalisation_DraftM36

1.2 Articulation in CODECS

WP4 is strongly related with other work packages of the project:

- with WP2, which has defined the general framework and to which WP4 provides methodologies and guidelines (Handbook of Methodologies),
- with WP3, which provides information and models of the processes before and after digitalisation, useful to carry out Life Cycle Assessment (T4.3),
- with WP5, in which demo events are a space for both data collection and presentation of the results to the stakeholders,
- with WP7, where the platform supplies WP4 analysts with genuine data collected in the Living Labs and where WP4 provides WP7 with assessment data. Both collaborate to design and create an interactive and attractive presentation of assessment results, through Economic Cost Calculator (ECC) and Environmental Footprint Calculator (EFC) in order to raise awareness and help farmers and policy makers in their choices,
- with WP8, especially the Living Labs coordination, as the analysis provided by WP4 strongly involve data to be collected in the Living Labs and also provides them with valuable information to share with the LL's stakeholders.

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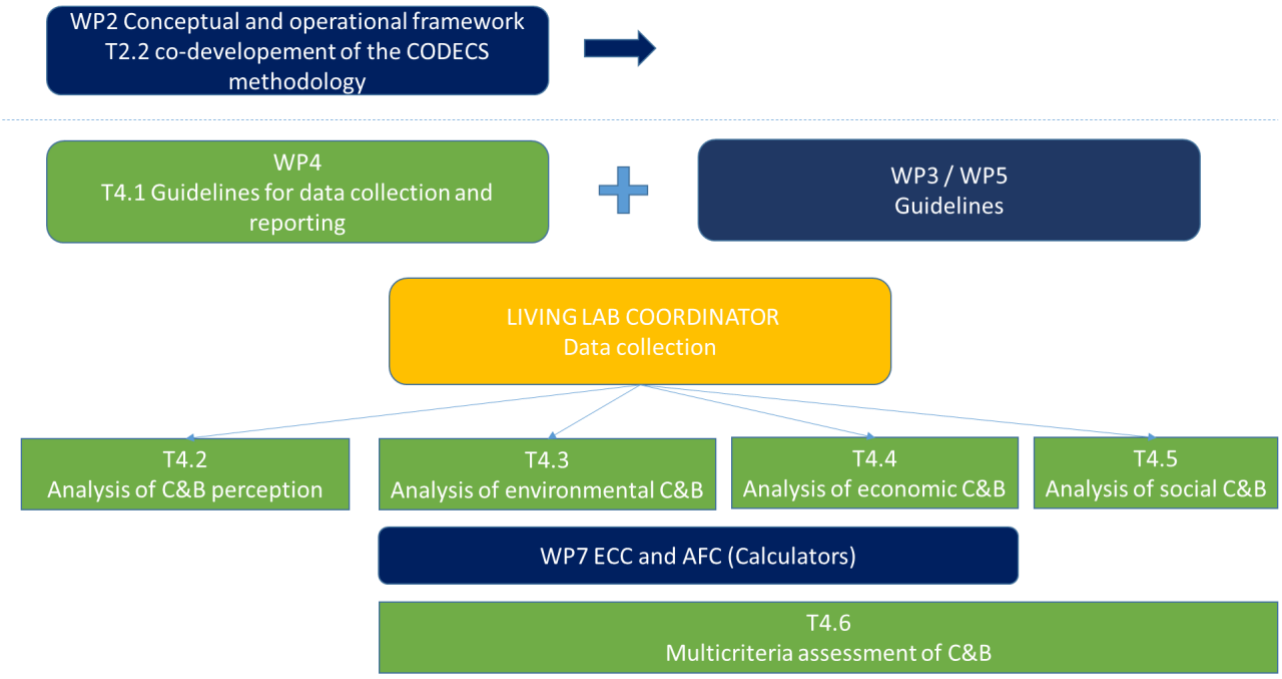

Figure 1: Articulation of WP 4 tasks

1.3 Advances of WP4 (M36 – M46)

This period (M36 – M46) was devoted to finalising the analyses conducted as part of the various Tasks. For Task 4.2, a new series of workshops held in the Living Labs made it possible to collect new data on stakeholders' perceptions of the costs and benefits of using digital technologies in agriculture (second focus group). This new data is being compared with the analyses produced previously. For the assessment of environmental (T4.3), economic (T4.4), and social costs and benefits (T4.5) – for each relevant living lab (LL) and, therefore, each specific use case – the analyses resulted in individual reports as well as initial general findings. These reports for each LL are designed to provide LL stakeholders with scientifically sound information, enabling them to subsequently discuss the challenges posed by digitalisation within their specific contexts. This was the case, in particular, during several demonstration activities (WP5).

This period also provided an opportunity to publish scientific articles and participate to conferences, for example at the CORDIALL conference (https://cordiall.sciencesconf.org/), which dedicated a special session to CODECS' scientific findings.

In the following sections, we recall the theoretical background and methodologies implemented in each task and provide updated findings on the costs and benefits of farm digitalisation. Note that this report is still an incremental draft version of the previous deliverable which will lead to a final synthetic report.

Figure 2 show the different types of data collected in the different LLs, for each dimension (environmental, economic and social).

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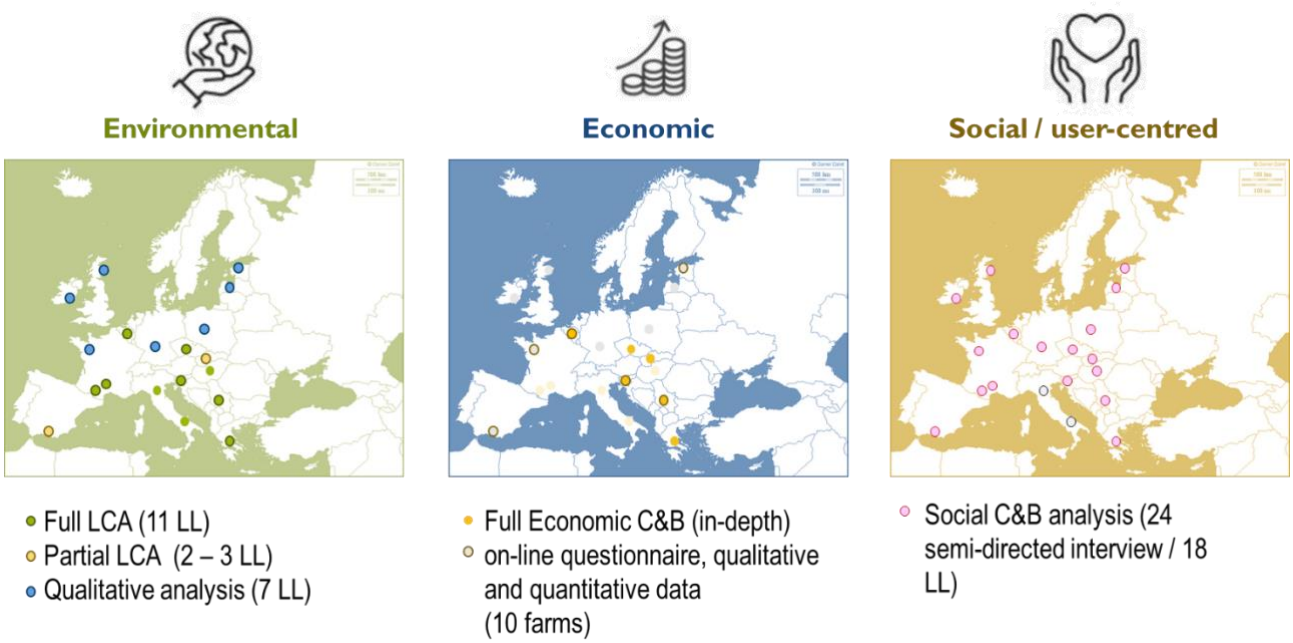

Figure 2 Data collected in the different LL for each sustainability dimension

2 Stakeholder perceptions of cost and benefits of digitalisation in agriculture (T4.2)

Authors: Constantine Iliopoulos, Irini Theodorakopoulou and Thomas Giotis (ELGO-DEMETER)

2.1 Introduction

The digitalisation of agriculture remains one of the central transformations affecting European agri-food systems. Digital technologies such as precision farming tools, remote sensing, unmanned aerial vehicles (UAVs), decision-support platforms, livestock monitoring systems, farm management information systems and digital market platforms are expected to support productivity, sustainability, resilience and improved working conditions (Finger, 2023; Shepherd et al., 2020). At the same time, their use raises questions about costs, data governance, skills, infrastructure, autonomy, responsibility and the distribution of benefits and burdens (Klerkx et al., 2019; Rotz et al., 2019; Regan, 2019; Carolan, 2017).

This section reports the final-year results of Task 4.2, which focuses on stakeholder perceptions of the costs and benefits (C&B) of farm digitalisation. It builds on the first-round focus group analysis reported in the previous deliverable and incorporates the second/final round of focus group discussions carried out in the Living Labs during the last year of the CODECS project. The value of the final-round analysis is that it allows perceptions to be examined dynamically: not only what stakeholders expected from digitalisation, but also how their views changed once technologies were further developed, demonstrated, tested, implemented, or experienced in practice.

The main conclusion is that stakeholder perceptions did not move in a simple positive or negative direction. Rather, they became more concrete, conditional and governance-sensitive. Stakeholders still recognised the potential of farm digitalisation for better decision-making, input optimisation, environmental benefits, market access and improved work organisation. However, they increasingly linked these benefits to enabling conditions such as advisory support, reliable data flows, interoperability, training, cost-sharing, trust in technology providers and clarity over responsibility and data use.

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2.2 Scope and Objectives

The scope of Task 4.2 is to capture qualitative, actor-centred insights into the perceived economic, environmental and social costs and benefits of digitalisation across the CODECS Living Labs. The final-year Focus groups extend the first-round analysis by adding a temporal perspective (Barnes et al., 2019). They examine how perceptions evolved as technologies moved closer to practical use or as stakeholders gained experience through demonstrations, pilot activities, workshops, data collection and Living Lab interaction.

The scope extends across three dimensions:

- geographical and sectoral diversity. The analysis covers 18 Living Labs across Europe, including arable, livestock, horticulture, viticulture, greenhouse, grassland, irrigation and local food market contexts.
- multi-actor engagement. Participants included farmers, advisors, policymakers, researchers, technology providers, cooperatives, producer organisations, digitalisation experts and other relevant actors, depending on each Living Lab context.
- temporal comparison. The paired first-round and final-round material allows comparison between initial expectations and later perceptions of materialised benefits, visible costs, unexpected problems, and changed levels of trust (Pathak et al., 2019).

The objectives of the final-year analysis are therefore:

1. to identify how stakeholder perceptions of farm digitalisation evolved between the first and final focus group rounds,
2. to compare expected benefits and costs with those that stakeholders perceived as having materialised in practice,
3. to analyse how costs and benefits are distributed among farmers, advisors, technology providers, value-chain actors, public authorities and society,
4. to identify recurring barriers and enabling conditions that should inform environmental, economic, social and multicriteria assessments in WP4,
5. to develop a Living Lab trajectory typology that captures different pathways of perception change rather than assuming a single linear adoption pathway.

2.3 Theoretical Background

The analysis is grounded in the understanding of agricultural digitalisation as a socio-technical transformation. Digital technologies do not produce costs and benefits independently of context. Their value depends on how they are embedded in farming practices, advisory systems, value chains, infrastructures, regulations, business models and trust relations. This is particularly important in agriculture, where farms differ widely in size, capitalisation, skills, production systems, market integration and exposure to climate and policy pressures (Zscheischler et al., 2022). Although CODECS focuses on digitalisation rather than mechanisation, wider research on agricultural technology change shows that technology adoption also reshapes labour, scale, skills and farm organisation (Daum and Birner, 2020).

The first-round findings already showed that stakeholders associated digitalisation with both opportunities and risks (Iliopoulos et al., 2025a). Expected benefits included efficiency gains, improved input use, better decision-making, environmental improvements, labour saving, traceability and new business models. Expected costs included investment costs, maintenance, skills gaps, data governance concerns, dependence on technology providers, interoperability problems and possible exclusion of smaller or less digitally prepared farms (Iliopoulos et al., 2025). The final-round analysis adds a dynamic dimension by examining what happens when these expectations are confronted with experience (Kernecker et al., 2020).

The theoretical contribution of the final-year analysis lies in moving beyond adoption as a binary decision. Stakeholders do not simply “adopt” or “reject” digital tools. They interpret, test, adapt, question and reframe them. The relevant question is therefore not only whether a technology is perceived as beneficial, but under what conditions, for whom, at what cost, with what support, and with what implications for data, autonomy and fairness.

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2.4 Methodology

2.4.1 Data collection and empirical material

Between October 2023 and January 2024, 18 LLs each organised Focus groups of 6–10 participants (farmers, advisors, policymakers, professors and in some cases technology providers, veterinarians and researchers). The discussions were structured around a common protocol (developed under Task 4.1 and included in the appendix).

Each group was presented with digitalisation technologies specific to its context (e.g. precision irrigation, UAV spraying, livestock monitoring). Participants discussed perceived costs, benefits, and challenges. Moderators recorded sessions, and transcripts were translated into English and submitted to ELGO-DEMETER by January 2024.

Three researchers independently coded transcripts and notes for perceived economic, social, and environmental impacts. Coding followed an inductive thematic approach, with open coding, cross-checking, and final reconciliation of categories. Themes were validated against existing literature and by participant feedback, which enhanced robustness.

The process followed these main steps:

- data collection: Focus group transcripts and notes gathered and categorised by country and Living Lab,
- initial coding: three researchers independently documented costs, benefits, and problems by theme (economic, social, environmental), including participant roles and technologies,
- cross-verification: entries were compared to ensure consistency and accuracy,
- open coding: transcripts were read multiple times; key words/phrases were highlighted and linked to themes,
- thematic categorisation: themes developed inductively from data, aligned with focus group questions,
- review & synthesis: researchers compared findings and agreed on final thematic categories.

The final-year analysis is based on paired qualitative material from the 18 CODECS Living Labs. For each Living Lab, the analysis used one paired file containing the first-round Focus group material and the final-round 2026 Focus group material. The paired files included metadata on the Living Lab, country, sector, digital technology, technology readiness level (TRL), date of each Focus group, number of participants, stakeholder categories, participant continuity and transcript status. In total, the dataset contains approximately 134.610 words of first-round material and 110.240 words of 2026 material. Known participant numbers amount to 172 participants in the first round, with 2 Living Labs reporting unknown first-round numbers, and 190 participants in the 2026 round.

Technology maturity also changed over time. In 11 Living Labs the reported TRL increased between the first and final focus groups, in 7 Living Labs it remained stable, and in 0 Living Labs it decreased. This variation is analytically important because the final-round focus groups did not capture the same stage of technology use everywhere. Some Living Labs discussed technologies that had become more mature or had been tested in practice, while others reflected on relatively stable or already advanced tools.

The final-round protocol was designed to capture perception change explicitly. Participants were asked what farm digitalisation meant to them “today”, whether their views had changed compared with two years earlier, which tools had been adopted or developed, what benefits and problems had materialised, which costs were most visible, who bears these costs, whether trust had changed, and what challenges or opportunities should be monitored in the next two years.

2.4.2 Data preparation and comparability assessment

Before coding, all paired files were checked for completeness and comparability. The assessment considered transcript status, participant continuity, stakeholder composition, word counts, technology maturity and the presence of both first-round and 2026 material. This step was necessary because not all Living Labs provided the same type or quality of material. Some files contained complete transcripts for both rounds, while others included partial transcripts, structured reporting tables, facilitator notes, or translated summaries.

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The analysis therefore distinguishes between different levels of evidence strength. Where the same or largely the same participants were involved and both rounds were documented in detail, stronger claims can be made about perception evolution. Where participant continuity was low or unknown, the analysis treats the material as a comparison of Living Lab discourse across two rounds, not as evidence that the same individuals changed their views. This distinction is important for methodological transparency.

Table 1 Evidence strength and comparability of the paired focus group material

Evidence category	Living Labs	Interpretation for longitudinal analysis
A. Strongest longitudinal evidence	New Edu (Slovakia); Smart Villages (Slovenia)	Complete material and high participant continuity. These cases support the strongest claims about perception evolution
B. Strong with qualification	Pecorino Toscano (Italy); Greenhouse LL (Serbia)	High continuity but partial transcript/reporting limitations, or a highly structured final-year record
C. Moderate longitudinal evidence	Agdibi (Germany); Greek LL (Greece); Ramas (North Macedonia); Appetit LL (Poland)	Medium continuity and/or partial baseline. Useful for Living Lab-level comparison; avoid individual-level claims
D. Cautious comparison	Agrifood ILVO LL (Belgium); Agroecology LL (Spain); Orchard LL (Czech Republic); Grassland (Estonia); Hutton LL (Scotland); Soil Scanner LL (Hungary); Latvian LL (Latvia); Lit Ouesterel (France); Occitanum Sheep LL (France); Occitanum Viti (France)	Low or unknown continuity and/or partial baseline. Interpret as repeated Living Lab discourse, not direct individual change

Note: The categories summarise the strength of evidence for longitudinal interpretation. They do not rank the substantive value of the Living Labs; they indicate how cautiously claims about "change" should be phrased.

2.4.3 Coding strategy

The coding followed a hybrid deductive-inductive strategy. Deductive parent codes were derived from the final-round focus group protocol and the analytical framework developed for Task 4.2. These codes captured changed perceptions, adoption/materialisation, expectation versus experience, economic and productivity benefits, labour and work-quality benefits, environmental benefits, decision/data benefits, financial costs, skills and learning burdens, technical and infrastructure costs, governance/trust/equity, policy/advisory support, distribution of costs and benefits, and future challenges/opportunities. Inductive subthemes were then identified within each parent code, such as data without interpretation, hidden maintenance costs, provider dependency, collective logistics, task-map frustration, farmer support needs and shared cost responsibilities.

The unit of analysis was a speaker turn, paragraph, table row or meaningful text segment. Very long paragraphs were split into smaller analytical segments when they contained multiple ideas. Each segment could receive more than one code because stakeholder statements often combined several dimensions, for example data benefits, technical barriers and trust concerns. Coding was used to identify salience and patterns across the corpus, while interpretation relied on close reading of the coded excerpts and attention to each Living Lab context.

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Table 2 Protocol-driven coding framework

Code family	Definition	Protocol questions
Changed perception	Direct or indirect evidence that stakeholders' views have changed, deepened, become more concrete, or been reframed since the first round	Q1, Q2, Q6, Q9
Adoption/materialisation	Evidence that tools were adopted, tested, further developed, implemented, used in practice, piloted, scaled, or failed to materialise	Q2, Q3, Q8
Expected vs experienced	Comparison between anticipated and experienced costs/benefits; matched or unmet expectations; unexpected effects	Q2, Q3, Q7, Q8
Economic/productivity benefits	Perceived economic, productivity, income, profitability, competitiveness, market or efficiency benefits	Q4, Q8
Labour/time/work-quality benefits	Labour saving, time saving, reduced workload, easier work, quality of work, safety, convenience, welfare, job security	Q3, Q4, Q8
Environmental benefits	Environmental sustainability benefits such as reduced inputs, reduced pesticides/fertiliser/water, biodiversity, soil, emissions, climate adaptation	Q4, Q8
Decision/data benefits	Benefits related to data, monitoring, mapping, decision support, real-time information, prediction, AI, analytics, platforms, traceability	Q2, Q3, Q4, Q8
Financial costs	Monetary costs: investment, price, affordability, subscription, maintenance, repair, replacement, return on investment, financial risk	Q5, Q6, Q7
Skills/learning burden	Skill, training, learning, digital literacy, complexity, interpretation, cognitive or administrative burden	Q2, Q5, Q7, Q10
Technical/infrastructure costs	Technical or infrastructural constraints: connectivity, reliability, interoperability, compatibility, data quality, breakdowns, sensor problems, platform integration	Q2, Q3, Q7, Q10
Governance/trust/equity	Trust, data governance, ownership, liability, autonomy, dependency, fairness, power relations, uneven distribution of costs/benefits	Q5, Q8, Q9
Policy/advisory support	Role of public policy, regulation, subsidies, advisory services, cooperatives, institutions, standards, public support and AKIS	Q2, Q4, Q6, Q9, Q10

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Code family	Definition	Protocol questions
Distribution of costs/benefits	Explicit distributional claims about who pays, who benefits, who bears costs/risks, and how costs/benefits are allocated across groups	Q5, Q6, Q8
Future challenges/opportunities	Forward-looking challenges, opportunities, needs, next steps, future policies, next two years, future adoption pathways	Q10

2.4.4 Longitudinal interpretation

The longitudinal analysis compared the first-round and 2026 material in three complementary ways. First, it examined changes in code salience across the whole corpus. Second, it compared how individual Living Labs discussed the same topics across the two rounds. Third, it developed a trajectory typology that captures qualitatively different pathways of perception change. The code counts were used as orientation, not as statistical proof. The final interpretation was based on the combination of coded salience, illustrative excerpts, evidence strength and Living Lab context.

This means that the results should be read as qualitative comparative findings. They reveal how stakeholders framed digitalisation and how these framings evolved, but they do not measure objective farm-level impacts. Objective economic, environmental and social impacts are addressed in other WP4 tasks. The contribution of T4.2 is to show which costs and benefits matter to stakeholders, which conditions shape acceptance, and how perceptions shift as digitalisation moves from expectation to experience.

2.5 Results update

2.5.1 Results from the first-round data collection

ELGO-DEMETER analysed the Focus group transcripts and facilitator notes from the first year of Focus group discussions held in the Living Labs, exploring the perceptions of various stakeholders regarding the costs and benefits of farm digitalisation.

The initial findings of this analysis were included in Deliverable D4.1. A subsequent, more comprehensive analysis yielded additional insights, which were presented in Deliverable D4.2 and formed the basis for two publications: one in a leading academic journal and another in the form of a Policy Brief aimed at a broader audience.

- Iliopoulos, C., Theodorakopoulou, I., Giotis, T., & Brunori, G. (2025). Perceptions of costs and benefits of farm digitalisation in Europe. International Food and Agribusiness Management Review, 1(aop), 1–22. https://brill.com/view/journals/ifam/28/3/article-p543_4.xml
- Iliopoulos, C., Theodorakopoulou, I., Giotis, T., & Brunori, G. (2025). Perceptions of the Costs and Benefits of Farm Digitalisation in Europe. EuroChoices. https://doi.org/10.1111/1746-692X.12471

Across 18 Living Labs situated throughout Europe, a comprehensive mapping of stakeholders was conducted, encompassing a wide variety of farming systems – including arable, livestock, horticulture, viticulture, and mixed operations – as well as diverse socio-economic contexts. Between October 2023 and January 2024, 148 participants took part in structured focus groups. These participants represented a broad spectrum of the agricultural sector: farmers, advisors, policymakers, technology providers, and researchers all contributed their perspectives.

The discussions revealed several key perceived benefits associated with the digitalisation of agriculture. Participants frequently highlighted improvements in efficiency, productivity, and decision-making as major advantages. The adoption of digital tools was also seen as a means to optimise the use of critical resources such as inputs, water, and energy. Environmental benefits were noted as well, with many pointing to reduced emissions and lower chemical

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usage as positive outcomes. Additionally, digitalisation was credited with making farming more attractive to younger generations and fostering innovation within the sector.

However, the focus groups also brought to light a number of significant costs and barriers. High investment requirements, ongoing maintenance, and subscription costs were commonly cited as obstacles to adoption. Participants expressed concerns about the lack of interoperability between systems and persistent connectivity issues, both of which can hinder the effective use of digital technologies. Data governance and ownership emerged as important issues, with stakeholders voicing worries about who controls and benefits from agricultural data. The need for ongoing training, advisory support, and skills development was also emphasised, as was the challenge of ensuring equitable access to digital tools across different regions and farm sizes.

Notably, the insights gathered revealed some regional differences in priorities and concerns. In Northern and Central Europe, there was a strong focus on achieving efficiency and precision gains through digitalisation. In contrast, participants from Southern Europe placed greater emphasis on inclusivity, building trust, and supporting social modernisation within their agricultural communities.

2.5.2 Results from the second round of focus groups

Due to the late finalisation of some LL workshops, the full and comparative analysis of the second round of focus groups will be provided in the last and final deliverable (M48).

2.6 Discussion

The analysis of stakeholder perceptions reveals that digitalisation in agriculture is widely recognised as offering considerable opportunities, but it is also surrounded by structural challenges that shape adoption and distribution of benefits.

A consistent finding is that perceived benefits focus on efficiency, productivity, and improved decision-making. Participants reported that digital tools allow more precise and timely interventions, reduce input use, and support better risk management and long-term planning. These observations are consistent with prior research that emphasises digitalisation's potential to enhance farm competitiveness and resource efficiency (Barnes et al., 2019; Getahun et al., 2024; Van Evert et al., 2017). Stakeholders also linked digitalisation to environmental improvements, particularly reduced pesticide and fertiliser use, aligning with studies highlighting its sustainability potential (Garske et al., 2021; Finger, 2023). Moreover, digitalisation was associated with new business models and social benefits, including service-based innovation and a perception that farming becomes more attractive to younger generations (Regan, 2019; Shehrawat et al., 2024).

At the same time, concerns were prominent, particularly around trust and governance. Farmers frequently raised questions about data ownership, contractual transparency, and accountability of technology providers. These findings echo the broader literature on agricultural digitalisation, which has consistently identified data rights and governance as central barriers to trust (Carolan, 2017; Klerkx et al., 2019; Arcuri et al., 2023). The perception of hidden or ongoing costs, lack of interoperability, and insufficient after-sales service further reinforce scepticism toward providers, mirroring adoption studies that highlight the importance of fair cost structures and reliable advisory support (Deichmannet al., 2016).

Another major theme is the time and resource burden of digitalisation. Stakeholders reported steep learning curves, additional training needs, and dependency on external expertise. While digitalisation promises efficiency gains in the long run, in the short term it may impose labour and knowledge constraints, particularly on smallholders with limited access to training and advisory services. Similar concerns have been documented in empirical studies on adoption barriers in Europe (Kernecker et al., 2020; Shehrawat et al., 2024).

From an environmental perspective, while stakeholders expect positive impacts, they also expressed scepticism regarding energy demands and rebound effects. The literature warns that efficiency improvements may paradoxically incentivise intensification, offsetting sustainability gains (Ajena et al., 2022; Hidalgo et al., 2023). This tension illustrates the complexity of positioning digitalisation as an unambiguous sustainability solution.

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Socially, digitalisation is perceived as a double-edged sword. On the one hand, it can improve working conditions and create new opportunities for youth and women in agriculture (Regan, 2019). On the other, it risks contributing to de-skilling of traditional knowledge and exacerbating digital divides between large, well-capitalised farms and smaller, resource-constrained holdings (Rotz et al., 2019; Hackfort, 2021).

Overall, the discussion confirms that perceptions of digitalisation are shaped by more than technical performance. They are embedded in social, economic, and governance contexts, where issues of fairness, trust, and inclusivity determine whether digitalisation is seen as an opportunity or a threat. The heterogeneity across regions reinforces this conclusion: Northern and Central European stakeholders emphasised technical efficiency, while Southern European groups highlighted inclusivity and social modernisation effects (Iliopoulos et al., 2025). This suggests that digitalisation cannot follow a uniform pathway in Europe but requires context-specific governance and support strategies.

2.7 Conclusion

Overall, stakeholders perceive digitalisation as offering significant opportunities for efficiency, sustainability, and new business models, but also as a source of risks and inequalities if governance and support structures are insufficient. The evidence underscores that benefits will not be evenly distributed without targeted interventions.

The study contributes to ongoing debates on agricultural innovation by documenting how farm-level experiences intersect with systemic challenges such as data rights, resource needs, and capacity building. It also establishes a methodological foundation for the forthcoming Multi-Criteria Assessment in WP4.

2.8 New activities between M36 & M46

During the period between M36 and M46, Task 4.2 moved from first-round perception analysis to final-round longitudinal analysis. The main activities were:

- preparation of the final-round Focus group protocol, including questions on changed perceptions, materialised benefits, visible costs, trust and future challenges,
- implementation of final-round Focus group discussions in the CODECS Living Labs during the last year of the project,
- collection and harmonisation of paired first-round and final-round focus group material from 18 Living Labs,
- preparation of Living Labs metadata, including participant numbers, stakeholder categories, technology maturity and transcript status,
- completeness and comparability assessment of the paired material, with attention to participant continuity and evidence strength,
- development of a protocol-driven coding framework and coding matrix,
- coding of the paired material and synthesis of cross-case changes in benefits, costs, trust, governance, distributional issues and future challenges,
- development of a Living Lab trajectory typology to support final WP4 integration and policy interpretation.

2.9 Upcoming activities

The remaining activities of Task 4.2 should focus on validation, integration and dissemination. First, the trajectory classifications and key findings should be reviewed with Living Lab coordinators where feasible, especially in cases with partial transcripts or low/unknown participant continuity. Second, the coded findings should be linked to the environmental, economic and social analyses in WP4, so that stakeholder perceptions are not separated from assessment results. Third, selected quotations and trajectory summaries can be used in stakeholder feedback materials, policy briefs and the final multicriteria assessment.

For D4.4 and the final stages of CODECS, particular attention should be given to trade-offs that stakeholders repeatedly identified: private costs versus public benefits, data-driven efficiency versus farmer autonomy,

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environmental ambition versus implementation burden, and innovation speed versus advisory and regulatory capacity. These trade-offs provide a bridge between perception analysis and the broader multicriteria assessment of farm digitalisation.

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3 Environmental assessment of farm digitalisation (T4.3)

Authors: Alexia Gobrecht, Véronique Bellon-Maurel, Baptiste de Massé, Clémence Huck (INRAE), Karine Dufossé (Institut Agro)

3.1 Introduction

Digital technologies are profoundly transforming the economic sectors in which they are adopted, with significant repercussions on their environmental impacts. Researchers have developed frameworks to categorise both the positive and negative environmental changes driven by digitalisation. However, despite growing interest, the specific environmental impacts of digital agriculture remain poorly understood.

Life Cycle Assessment (LCA) is a standardised, widely adopted method for evaluating the environmental impacts of products and services across all economic sectors. It employs a multi-criteria approach, examining the entire life cycle from raw material extraction to end-of-life disposal. To address the gap in quantitative assessment, LCA is proposed as the method for evaluating the environmental impacts of digital agriculture.

In the context of CODECS, the environmental impacts of digitalisation in agriculture are analysed at the agricultural process and/or farm level using LCA. This approach allows for a comparison of the environmental footprint of agricultural production processes before and after the adoption of digital technologies. The adoption and use of digital technologies introduce changes in the production process, which in turn may alter its environmental impacts compared to the original (reference) scenario. These changes are captured through comparative LCA of the two processes – before and after digitalisation.

The results of these LCAs provide valuable insights for farmers, advisors, and service providers regarding the real-world environmental impacts of digitalisation. They also help identify hotspots – steps in the process with particularly high environmental impacts. The environmental assessment in CODECS utilises quantitative data collected from farms in various Living Labs (LL), as well as data from the literature and databases.

Following a brief introduction to LCA methodology and a synthesis of the state of the art conducted during the first phase of CODECS, this chapter outlines the methodology implemented in CODECS to assess the environmental impacts of farm digitalisation based on the use-cases of CODECS' Living Labs. As data collection and analysis are ongoing, this deliverable will present the type of results that can be obtained, using the Slovenian Living Lab as a pilot use-case.

3.2 Introduction to Life Cycle Assessment

Life Cycle Assessment (LCA) is a standardised, ISO-compliant methodology (ISO 14040/44) widely applied to quantify the environmental impacts of products, services, and systems – including food and agricultural systems (Boschiero et al., 2023; Poore & Nemecek, 2018) as well as digital technologies (Arushanyan et al., 2014). As such, LCA provides a robust framework for evaluating the environmental footprint of digital solutions deployed in agriculture.

LCA systematically inventories all material and energy flows associated with a product or process across its entire life cycle – from resource extraction ("cradle") through production, use, and end-of-life ("grave") (Figure 3: Scope of the LCA). This "cradle-to-grave" approach ensures a comprehensive assessment of environmental burdens and emissions, including those from energy production, operational activities, and waste management.

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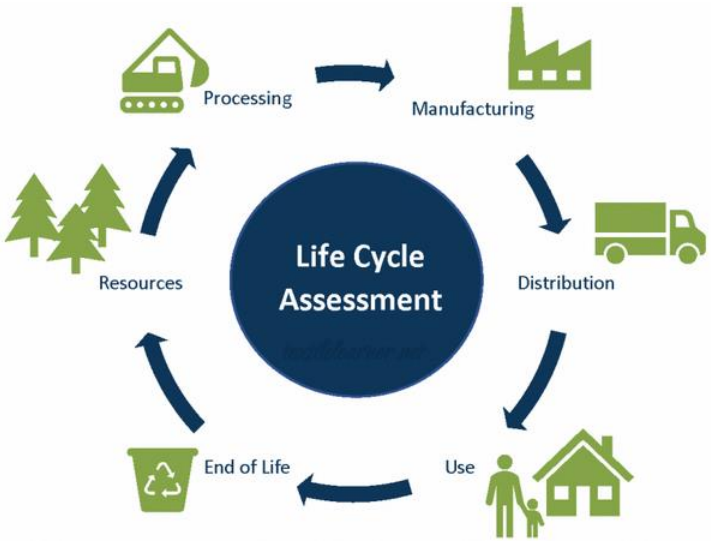

Figure 3: Scope of the LCA

The method employs a multi-criteria analysis, enabling the evaluation of impacts across diverse categories such as global warming potential, ecotoxicity, resource depletion, and water use (Figure 4). By quantifying inputs (resources, energy) and outputs (emissions, waste), LCA characterises and aggregates potential environmental impacts, providing a holistic view of a product or system sustainability performance. This granularity and scope make LCA particularly suited for identifying hotspots and informing mitigation strategies in complex systems like digital agriculture.

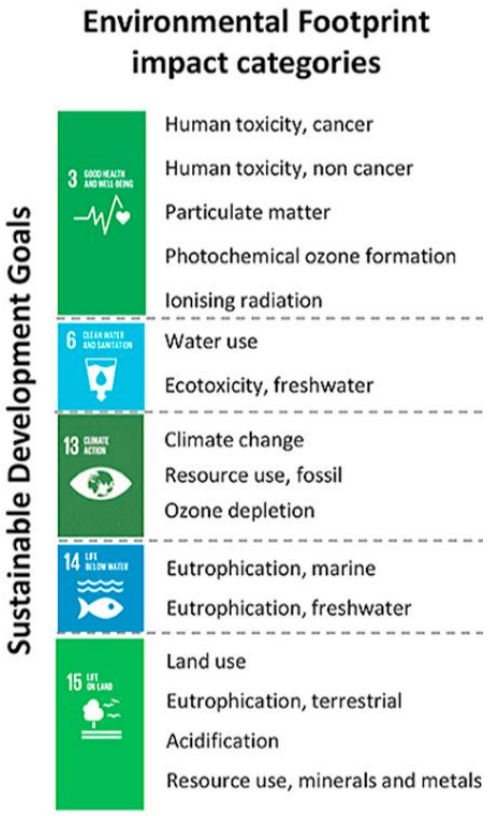

Figure 4: Environmental impact categories in LCA (and link to the SDG)

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The LCA methodology follows several steps (Figure 5) allowing to state the goal of the study, describing the involved processes, collect the data and calculate the impacts along diverse impact categories:

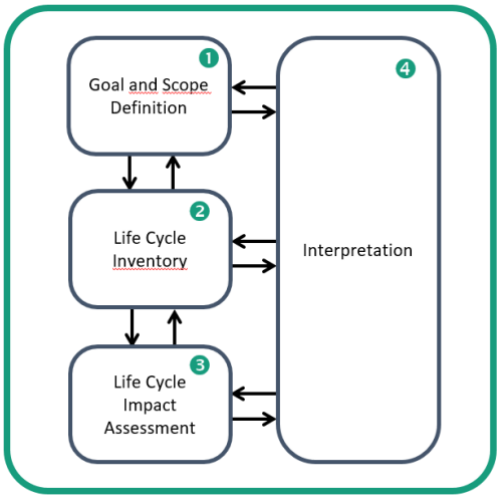

Figure 5: LCA steps

- Goal & Scope: Definition of the objectives and boundaries of the system under study,
- Life cycle inventory: inventory of from and to the ecosphere for a system – it involves quantitative data collection on the processes under study,
- Impact assessment: this phase aim at evaluating the potential environmental and human health impacts resulting from the flows identified for the system under study,
- Interpretation: identifies, quantifies, checks, and evaluates information from the results of the life cycle impact assessment. The outcome of the interpretation phase is a set of conclusions and recommendations for the study.

Although this method presents a precise framework, its application to the context of digital agriculture is relatively recent. The following chapter therefore presents a summary of the state of the art on Environmental assessment of digitalisation in agriculture and how the LCA methodology has been applied to processes involving digital agriculture technologies.

3.3 Environmental assessment of digitalisation in agriculture: state of the art

Prior to the case studies conducted in CODECS Living Labs, a state-of-the-art review was published on the environmental assessment of the impacts of digitalisation in agriculture.

Huck, C., Gobrecht, A., Salou, T., Bellon-Maurel, V., & Loiseau, E. (2024). Environmental assessment of digitalisation in agriculture: a systematic review. Journal of Cleaner Production. (10.1016/j.jclepro.2024.143369).

This article systematically reviews the environmental impacts of digital agricultural technologies (DAT) and examines these impacts using the Life Cycle Assessment (LCA) framework.

It sheds light on the methodological challenges involved in assessing the environmental impacts of digitalised agricultural systems and enabled the consistent application of LCA to CODECS use cases.

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3.4 LCA Methodology applied in CODECS

3.4.1 Comparative Life Cycle Assessment

To analyse the environmental impact of digitalisation in agriculture and gain a better understanding of the factors that contribute to this impact, the project is based on comparative Life Cycle analyses carried out on the farms of the CODECS Living Labs.

The principle is to assess the environmental impact of a non-digitalised process (same business as usual, referred to the reference process) and compare it with the same process that implements digital technology (referred as the digitalised process) (Figure 6).

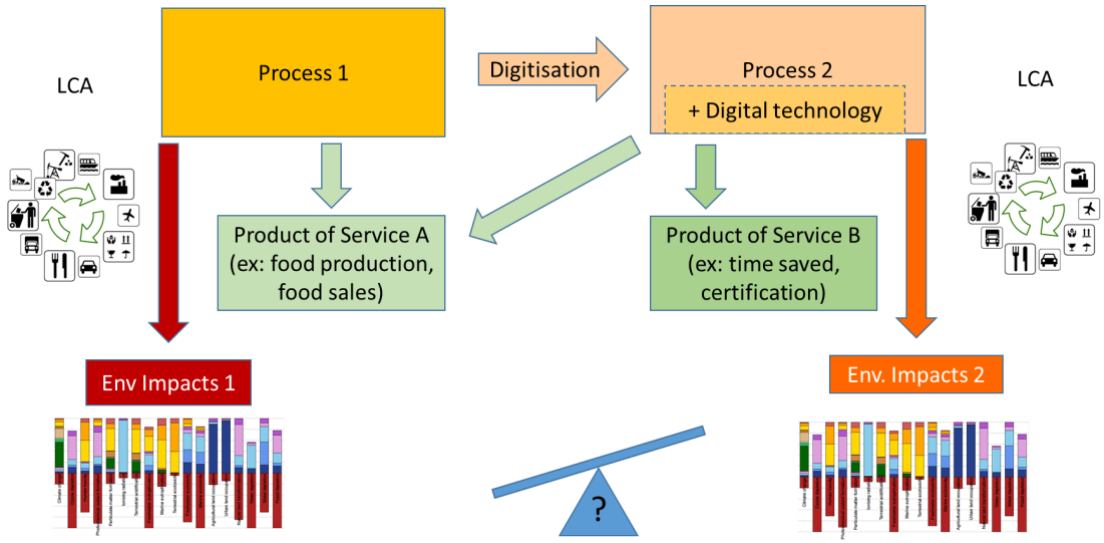

Figure 6: Principles of comparative LCA in the context of farm digitalisation in CODECS

For each scenario, the LCAs generate results across 16 midpoint impact categories (e.g., climate change, resource use, human toxicity, eutrophication, water use) which can subsequently be aggregated into endpoint indicators describing potential damages to Human Health, Ecosystems, and Resources. These LCAs make it possible to provide answers for each analysed living lab to the following questions:

- what are the environmental impacts of the 2 processes?
- how and to what extent does the use of the digital technology transforms the processes (e.g. technical itineraries)
- which part of the process contributes the most to the environmental impacts?

3.4.2 Use-case selection in CODECS LLs

In order to study the environmental impact of farm digitalisation, it is necessary for them to have already implemented the technologies and adapted their processes. Given that the various CODECS Living Labs use cases are not at the same level of digitalisation, – implementing technologies at different stages of deployment and maturity – a set of criteria was proposed to select the use cases most suitable for conducting Life Cycle Assessments (LCAs). These criteria are:

(i) **State of digitalisation**:

- Not digitalised: the technology or its functions are identified but still at a low Technology Readiness Level (TRL), in the prototype phase,

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- Digitalising: the technology is being used, either in experimental or pilot farms, and/or the technology is not yet fully developed and is still in the testing phase.
- Digitalised: the technology is routinely used in multiple commercial farms.

(ii) **Transformative degree of its use**: does the integration of the technology into the agricultural production system introduce observable and measurable transformations (changes in practices, input quantities, yields)?

(iii) **Data availability**: the Living Lab's capacity to provide technical data for both the reference scenario and the digitalised scenario.

Based on these criteria, the Living Labs were classified according to the feasibility of conducting LCAs on their use cases (Table 3 LL Classification and Type of environmental analysis):

Table 3 LL Classification and Type of environmental analysis

Comparative LCA	Simple/ Partial LCA	No LCA (qualitative analysis)
Agrifood Technology (BEL) Smart Villages Network (SLO) Occitanum Viti 81 (FRA) RAMAS (NMA) Innovative Soil Scanner (HUN) Orchard Management (CZE) Greenhouse Smart sensor (SER) Organic vineyard, SPATA (GRE)	Irrigation (SLK) Occitanum Sheep (FRA)	Appetit (POL) Remote rural farming communities (SCO) Cloughjordan Food Hub (IRE) LIT Ouesterel (FRA) Grassland Management (EST) AgriDiBi (GER) Living Lab Latvia (LAT) Almeria Agroecology (ESP) Pecorino Toscano (ITA) Organic Table Grape (ITA)

3.4.3 Data collection steps for the Life Cycle Inventory (LCI)

In order to carry out the Life Cycle Inventory (LCI) stage, several sources of data are available:

- data from the LLs produced for the other work packages in the project, mainly WP3, describing the processes used, the technology, etc.,
- data from interviews with farmers, which enable the quantitative data to be adjusted to real usage situations,
- data from existing databases and references.

On-field emissions into the environment were then calculated using the **Means In-Out** tool developed by INRAE (Auberger et al., 2013). The **OLCA-Pest model** is used of for pesticide emissions to soil, air and water (Nemecek et al., 2022). Phosphorus and heavy metal emissions are calculated using the **SALCA model** (Nemecek et al., 2024).

After collecting data from the local authorities, for each documented use case, we conducted a comparative Life Cycle Assessment to generate impact indicators.

3.4.4 Life Cycle Analysis on CODECS Use-Cases

10 Living Labs were able to collect the data needed to conduct a comparative Life Cycle Analysis. For each LL, the following materials were produced with the aim of providing LL coordinators and stakeholders with resources to facilitate discussions on the digitisation of agriculture:

- a PowerPoint synthetising the LCA on the use-case following the methodology (Goal and Scope, Scenario description, LCI, results, conclusion),
- a LCA report with more details on the findings,
- an excel file with the Data collected and the LCA indicators.

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From the analysis, the specific goal for the LLs was to provide answers to the following questions:

- **How do the environmental impacts of a production process change when implementing a digital technology?**
  - Is digitalisation changing the environmental impacts of the production process?
  - How does digital technology contribute to these impacts?
  - Which part of the production process contributes the most to the impact?
- **How does the use of these technologies modify farming practices and thus the overall impact of production?**

After validation of these documents by the LL coordinators, they will be uploaded in the CODECS Platform and also in the Zenodo Repository (Example).

Figure 7 LCA analysis of CODECS LL use-cases illustrates the various technologies implemented, as well as the associated production systems. Among them, 7 Living Labs implemented IoT and sensor technologies for the purpose of managing inputs, and 3 Living Labs tested drones or automation tools.

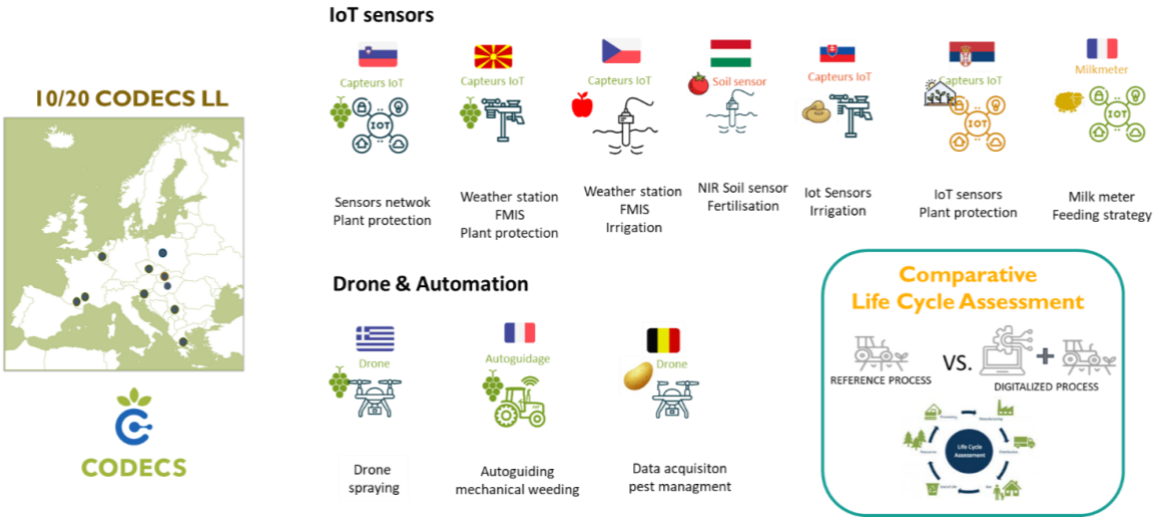

Figure 7 LCA analysis of CODECS LL use-cases

The related datasets comprising **10 final Life Cycle Analysis reports** produced by INRAE and the LL as part can be visualizes in the Zenodo Repository : 10.5281/zenodo.21645446

For each LL, a zip folder contains the LCA report of the study on the environmental impacts of the use of digital technologies on a farm of a CODECS Living Lab, a Power Point presentation for the stakeholders and an Excel file with the results data of the LCA.

3.5 General findings from the LCA on 10 Use-Cases

Initial analyses of CODECS use cases enabled us to develop some general findings, which were presented at the CORDIALL conference in April 2026 during the special session on CODECS.

- Digital Agriculture Technologies, or DAT, are transforming farms by modifying inputs, yields, and energy use. While they are promoted as a way to reduce agriculture's environmental footprint, tensions remain unresolved. On one hand, the technology itself has an environmental cost – think of the hardware, the networks, and the energy required for data storage. On the other hand, the real environmental impacts triggered by these tools is often undocumented.
  Our core question is: "does DAT adoption change the environmental impact because of the technology itself, or because of the changes in farming practices it triggers?"

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- The most significant finding is that in all 10 use-cases, digitalisation reduced the overall environmental impacts. These gains were primarily driven by factors such as input optimisation, yield increases, or decrease in tractor use. However, half of these positive results are mitigated by the fact that the impact reduction is less than 10%, which is not considered significant in LCA results.
  Furthermore, it's not all perfect. Some technologies caused an increase in specific categories, such as mineral resource use and ionising radiation, directly related to the life cycle of the DAT themselves. (Figure 8 Effects of using digital technologies on the environmental impacts (based on 10 LCA))

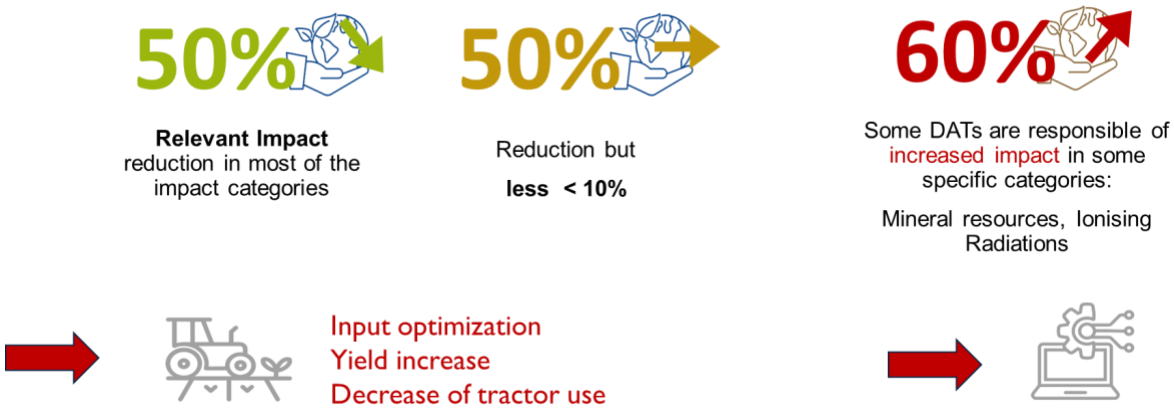

Figure 8 Effects of using digital technologies on the environmental impacts (based on 10 LCA)

- Digital technologies themselves contribute very little to the total environmental impact, compared to the agricultural process.

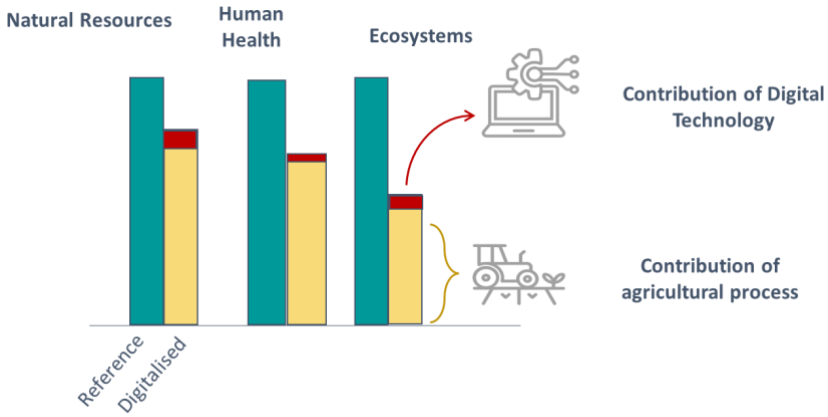

Figure 9 Contribution of the digital tool to the overall impacts (compared to the agricultural process contribution)

- The real power of these tools lies in how they change farming practices. This leads us to a new, vital question: To what extent will these technologies trigger changes to the most impactful steps of the agricultural process? We've learned that the technology is just the lever; the actual environmental 'margin of progress' depends on how much the tool can transform the most environmentally impacting parts of the farming processes."

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3.6 Qualitative analysis of environmental impacts in the other use-cases

For the LLs that were unable to provide quantitative data (see criteria), a qualitative analysis was conducted on the data collected through other tasks within the WP: the focus group transcripts (T4.2) and the interviews conducted at the farm level in task T4.5 (Social C&B).

For each LL, verbatim comments related to the topic of the environment were extracted and categorised.

This work is still to be finalised and will contribute to the synthetic report on environmental Costs and Benefits at farm level.

3.7 Forthcoming steps

- M46 – M48: Report on Environmental analysis based on qualitative data (perception and in-depths interview of T4.5) to extract Environmental analysis of the LL where it was not possible to perform an LCA
- Practice Abstract (20 LL)
- Contribute to the final deliverable and policy brief
- Organising data in CODECS platform
- Communication & scientific valorisation

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4 Economic costs and benefits assessment of farm digitalisation (T4.4)

Authors: Alexandra Sintori, Thomas Giotis (ELGO-DEMETER)

4.1 Introduction

The current chapter reflects the contribution of Task 4.4 of CODECS, entitled "Analysis of Economic Costs and Benefits", which is dedicated to the identification and estimation of the economic costs and benefits that stem from the adoption of digital technologies in farming. Digitalisation is increasingly promoted as a lever for a more productive, resource-efficient and resilient European agriculture. Yet, for the individual farmer, the decision to adopt

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a digital technology (DT) remains, first and foremost, an economic decision: it requires an upfront investment and changes the structure of operating costs and revenues in ways that are often uncertain and difficult to anticipate.

This document brings together, the application and the main findings of the economic analyses carried out across the CODECS Living Labs. It presents the scope and objectives of the economic Cost and Benefit (C&B) assessment, the methodological framework that was developed and applied, and the two complementary data-collection surveys (an online survey and in-depth farm interviews). It then describes how data collection progressed across the network and provide some preliminary findings emerging from the completed analyses.

Throughout the implementation period of the project detailed in-depth economic analyses have been completed for nine Living Labs: Belgium, Czech Republic, Greece, Hungary, Italy, Serbia, Slovenia, Slovakia and North Macedonia, while four additional Living Labs, Latvia, Spain, France and Estonia, have contributed data through the online survey only, providing predominantly qualitative and a limited amount of quantitative information. Together, these thirteen cases cover a wide range of production systems (arable crops, viticulture, orchards, protected horticulture and livestock) and a broad spectrum of digital technologies (sensor networks, drones, decision-support systems, farm-management information systems, precision and automated irrigation, and soil/crop scanning). The synthesis therefore offers a rare, empirically grounded picture of the economics of on-farm digitalisation in Europe. In addition, a further group of Living Labs, for which farm-level economic data have not been collected within Task 4.4, is included on the basis of the anticipated costs and benefits identified using data from CODECS Task 3.3 on process-modelling and Task 4.2 focus-groups, broadening the coverage towards digital marketplaces and short food supply chains.

4.2 Scope and Objectives of Economic C&B assessment of farm digitalisation

Task 4.4 focuses on the identification and assessment of the economic costs and benefits that derive from the digitisation, and consequently the digitalisation, of farming. Digitalisation offers farms a wide array of potential benefits: enhanced productivity, input savings, improved product quality and better risk management, but it also entails costs that go well beyond the purchase price of the equipment. The task aims to make both sides of this equation explicit and, wherever the data allow, to quantify them.

The specific objectives of the economic analysis are to:

- identify **the main cost and benefit items** associated with the adoption of digital technologies at the farm level, distinguishing between transition (investment) costs and operational (annual) costs and benefits,
- **quantify** these costs and benefits for the Living Lab case studies where sufficient data are available, and assess the economic viability of the investment through budget and Net Present Value (NPV) analysis,
- reveal the **key elements, barriers and bottlenecks** of the digitalisation process and identify ways to address them,
- provide information that can support **farmers and their advisors** in making adoption decisions, and feed into web-based decision tools developed within the project.

The economic costs and benefits estimated in Task 4.4 are meant be integrated into the Multi Criteria Assessment of Task 4.6, where trade-offs across economic, social and environmental dimensions will be examined. The methodological framework, the data-collection materials and questionnaires, the case studies and the results of the economic analysis also facilitate the development of the economic cost and benefit calculator of the CODECS assessment toolkit. They will be made available to policy makers designing and implementing measures for farming digitalisation (contribution to Policy Brief 9: Economic co-benefits and costs of digitalisation).

4.3 Methodological framework

Digitalisation is perceived by farmers and agri-food stakeholders to hold many economic benefits, such as enhanced productivity and profitability of farms and a reasonable return on investment (Abdulai et al., 2024; Gangwar et al., 2022). At the same time, adoption is constrained by high investment costs, uncertainty about returns, and a range of "hidden" transaction, learning and regulatory costs (Ferrari et al., 2022; Visser et al., 2021).

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Within CODECS, the economic analysis focuses primarily at the farm level, as this is where decisions about adopting digital technologies are made and where the physical and economic effects of adoption materialise. The analysis considers both transition costs: the initial investment required to acquire, install and integrate the digital technology, and operational costs and benefits: the annual changes in production costs, input use, labour, output and revenue that follow adoption. The adopted framework follows a Cost/Benefit approach and relies more on ex-post evaluation of technologies that have already been adopted (Barrientos-Fuentes & Berg, 2013; Maredia et al., 2014), complemented, where necessary, by secondary data sources and expert judgement.

The economic analysis methodology is multistep and tailored for each Living Lab, according to the type of the digital technology applied, the type of production, the level of digitalisation and the availability of data. It aims at providing quantitative and qualitative information regarding the changes in economic indicators that the adoption of digital technologies brings in the farm and the production system.

Therefore, the economic analysis methodological framework involves a mixed-methods approach, based on both quantitative and qualitative data collected from the farms in the CODECS Living Labs, and utilises methodologies commonly used in agricultural economics. Figure 10 represents this proposed multi-step and data driven methodology for the economic analysis.

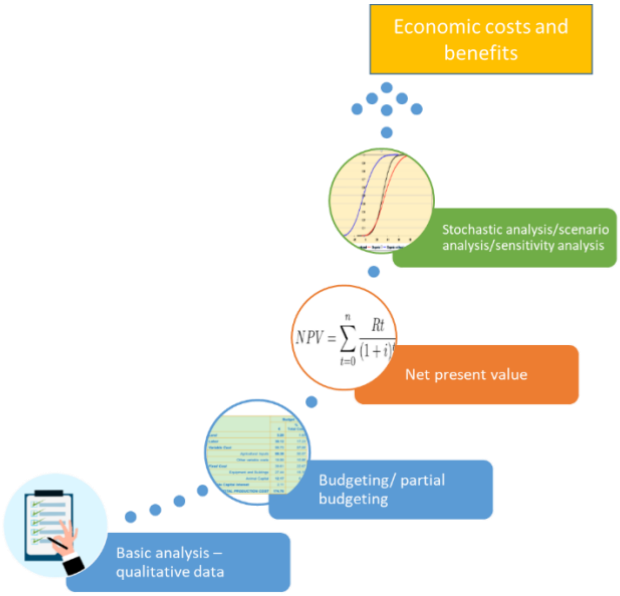

Figure 10 Mutli-step methodology for economic analysis, tailored for each LL

4.3.1 Basic economic analysis

The first level of the methodological framework utilises both qualitative and quantitative data. Where quantitative data at farm level are available, the basic economic analysis involves the estimation of the cost structure in the reference and the digitalised scenario as well as the estimation of profitability and productivity indicators. It utilises data provided by the LL facilitators through the CODECS Data Collection Framework (DCF). Productivity indicators are estimated as follows:

$$Labour\ Productivity = \frac{Production\ Value\ (€)}{Total\ Labour\ (hours)} \quad (1)$$

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$$Variable\ Capital\ Productivity = \frac{Production\ Value\ (€)}{Total\ Variable\ Capital\ (€)} \quad (2)$$

$$Fixed\ Capital\ Productivity = \frac{Production\ Value\ (€)}{Total\ fixed\ Capital\ (€)} \quad (3)$$

Labour productivity indicates how efficiently labour is transformed into output. It measures the economic value produced in one hour of work. High labour productivity also means that the farm uses the technology well, since it can produce more output with less effort.

Accordingly, variable capital productivity and fixed capital productivity measure how efficiently a farm uses its financial resources to generate output or revenue. Fixed capital productivity indicates how much revenue or output a business generates for every euro it invests in long-term, permanent assets. If the fixed capital productivity of the farm is low, then this means that the farm is over-capitalised. Variable capital productivity indicates how effectively a business generates revenue from the money it spends on short-term, operational inputs.

Profitability is also estimated as revenue minus costs[1], for both the reference and the digital scenario:

$$Net\ Profit\ (€) = Revenues - Costs \quad (4)$$

As previously mentioned, the productivity and profitability indicators can be used when quantitative data are available. Additionally, the basic economic analysis foresees a qualitative analysis that is applicable for all Living Labs (LLs), but focuses more to those that have not yet implemented fully the digital technology, and therefore no quantitative data for the reference and the digital scenario are available.

For the qualitative analysis, a concise and easy to complete on-line questionnaire was developed, that focuses on key questions related to transition and operational costs and benefits. The questionnaire has been developed based on:

- the existing literature,
- the D2.1 CODECS Conceptual Framework, which outlines the types of costs and benefits associated with the adoption of digital technologies,
- the results of T4.2 on the perceptions of costs and benefits of digitalisation (Iliopoulos et al., 2015).

The questionnaire consists of six sections concerning general information of the farm and the technology applied, initial investment costs, learning and training costs, transactions costs, changes in operational costs and in revenues.

As already explained, the purpose of the online questionnaire is to gather feedback from all LLs, even the ones that are not yet digitalised and cannot provide quantitative data. In the cases of LLs, that only qualitative data on economic costs and benefits can be provided, the basic analysis is limited to the presentation of the findings of the online survey on expected effects of the adoption of digital technologies on transition and production costs as well as farm revenues. In the digitalised LLs, this basic economic analysis complements the more detailed findings gathered from in-depth interviews.

4.3.2 Partial Budget analysis

The main step of the economic analysis involves the construction of a budget table that will reflect the changes in costs and benefits. Budgeting analysis is often used, to assist farmers in their decision-making regarding changes in production methods and adoption of new practices (Alimi, 2000; Munz, 2024), since it lets them compare economic costs and benefits before and after the adoption of the innovation or rather “with” or “without” the innovation. It is a

[1] In some cases, Gross Profit is estimated as Revenues minus Variable Costs

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very useful and easy to apply management tool that summarises additional input requirements and benefits, expressed in monetary terms either for the whole farm, a single enterprise or process within the farm. The construction of Budget Table also allows for the estimation of productivity indicators for main resource units (e.g., labour or land productivity) and economic outcome indicators like profit and income, in the cases that provide sufficient data (see for example Ahmed et al., 2021).

4.3.3 Net present value (NPV) analysis

Net Present Value (NPV) analysis is also performed in the cases that quantitative data are available. NPV is a commonly used and well-established methodology for cost-benefit analysis of the impact resulting from the adoption of technologies, practices and innovations (see for example Mburu et al., 2007; Wassmann and Pathak, 2007; Maredia et al., 2014; Mutenje et al., 2019). NPV sums up the discounted net cash flows (benefits minus costs) generated by the adopted digital technology over a period of time. This approach allows to estimate if the investment in the digital technology is viable and profitable. The basic formula for the estimation of the NPV is the following (Truitt, 1978):

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+r)^t}$$

where B_t=benefits at time t, C_t costs at time t, r=discount rate. According to the NPV criterion adopting digital technology is economically viable if the present value of benefits is greater than the present value of costs (NPV>0). It is evident that for the estimation of cash- flows required for the NPV, investment costs, input costs and benefits in the form of potential revenues is required (Medici et al., 2021). This information is available from the Budget Table, described in the previous paragraph.

Another advantage of using the NPV analysis is that this formulation can be used in web-tools for the adoption of technology (Medici et al., 2021). Therefore, this methodological step facilitates the development of the Economic Calculator planned in T7.4.

To account for economic risk, sensitivity analysis can be conducted, for basic variables used in NPV. Additionally, as previously explained, scenario analysis maybe performed to estimate alternative investment options.

Scenario analysis and sensitivity analysis allows to account for the socio-economic environment in which decision-making occurs. For example, governance system rules, such as subsidies on investment or production costs, may influence the adoption of digital technologies and can be incorporated into the economic analysis as alternative scenarios.

Additionally, factors that may hinder the adoption of digital technologies, such as a lack of legislation, legal restrictions, special permits, or requirements, can be included in the economic analysis, as they contribute to additional costs or impact other cost and benefit components.

4.4 Data collection

4.4.1 Two complementary surveys

For the economic analysis, two complementary data-collection surveys were carried out:

1. **Online data collection survey for economic costs and benefits.** As explained above, the online questionnaire supports the basic economic analysis and captures the main costs and benefits stemming from digital-technology adoption. A hard copy of the questionnaire was originally presented to the LL coordinators during the online training course held in February 2025. Following feedback from within the CODECS consortium, the questionnaire was finalised and distributed online to all Living Labs. A draft of the online

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questionnaire and all the relevant documentation can be found in the section and Access to on-line questionnaire here.

2. **Face-to-face in-depth interviews for technical and economic data.** Within the in-depth survey, data are collected at the farm level through farmer interviews organised by the Living Lab Coordinators. This approach provides access to accountancy records and detailed technical and economic data on the production system before and after digitalisation. To tailor the data-collection materials to each case study, one-on-one online meetings between the LL coordinators and the research teams of T4.3 and T4.4 took place in March 2025. The in-depth process for each LL involved: i) identifying the farm(s) to be assessed and checking their capacity to provide quantitative data ii) organising a 1–2 hour interview (ideally in person), iii) sending the questions in advance so that the farmer could locate the relevant records (e.g. log books), iv) conducting the interview with the help of the dedicated questionnaire, v) and completing the data-collection file.

   The data requirements met by the in-depth survey include estimates of annual land costs, agricultural input costs, labour, energy and water use, machinery operation, output quantities and quality, prices and income, both before and after the adoption of the technology. It is important to emphasise that only a small number of farms within the CODECS LLs had already adopted and used digital technologies at the time of the survey, the in-depth analysis therefore focuses on these adopters, complemented by expert judgement and secondary data where farm records were incomplete.

4.4.2 Progress of data collection

The online survey began in July 2025 and ran in parallel with the face-to-face in-depth interviews. As data collection progressed, the responses were reviewed for inconsistencies and, for the in-depth cases, coupled and analysed together with the online data and with secondary information (e.g. wage rates, input and energy prices, interest and discount rates) obtained by the research team.

Data collection has advanced to the point where **thirteen Living Labs** have contributed to the economic analysis, at two different levels of detail:

- **Nine Living Labs provided in-depth data** enabling the full framework of analysis: cost-structure analysis, partial budget and NPV. These LLs are Belgium, Czech Republic, Greece, Hungary, Italy, Serbia, Slovenia, Slovakia and North Macedonia.
- **Four additional Living Labs provided online data only**, i.e. predominantly qualitative and a limited amount of quantitative information: Spain, Latvia, Estonia and France submitted online-questionnaire responses that were written up as short qualitative individual reports. For these four LLs, only the basic (qualitative) analysis applies, and the results should be interpreted with caution given the small number of respondents.
- **A further group of Living Labs** took part in CODECS but have not provided farm-level economic data for Task 4.4. For these, only anticipated (qualitative) economic costs and benefits are available, drawn from reports and data from other tasks, i.e Task 3.3 socio-technical process modelling, the Task 4.2 focus groups and the Living Lab storybooks. For the French dairy-sheep case study, a partial Data Collection Framework covering the digital scenario only, was also utilised. Short individual reports have been prepared for each one of these Living Labs. They include Ireland (Cloughjordan Food Hub), Poland (APPETIT), Scotland (Hutton), Italy (Organic Table Grapes), France (Occitanum dairy sheep) and Germany (Agri-Digital Bildung).

Table 4 summarises the CODECS Living Labs, the technologies assessed, the production systems and the type of data they provided and utilised in the economic analysis.

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Table 4 Overview of the Living Labs contributing to the economic analysis

N.	Living Lab / Country	Production system	Digital technology assessed	Data type
1	Belgium (Agrifood Technology LL, ILVO)	Arable – potato	Imaging drone (RTK-GPS + camera) with AI detection for variable-rate precision spraying	In-depth + online
2	Czech Republic (Orchard management LL)	Orchard – apricot, cherry, pear	Soil & weather sensor network (LoRaWAN) for irrigation scheduling	In-depth
3	Greece (Spraying Drones LL, AUA)	Viticulture – vineyard	Spraying drone (DJI Agras T16, GPS)	In-depth
4	Hungary (Soil Scanner LL)	Arable – sunflower	NIR soil scanner for site-specific fertilisation	In-depth
5	Italy (Consorzio Pecorino Toscano LL)	Livestock – dairy sheep	Farm Management Information System / DSS (Poderi app, NIR analyser, ultrasound, RFID)	In-depth + online
6	Serbia (Greenhouse Smart Sensor LL)	Protected horticulture – radish, eggplant, kohlrabi	IoT sensor network (LoRaWAN) + AgroSens DSS platform	In-depth + online
7	Slovenia (Smart Villages Network LL – Doppler Winery)	Viticulture – vineyard	IoT sensor network (LoRaWAN) + ThingsBoard monitoring	In-depth + online
8	Slovakia (Artificial Irrigation Management LL)	Arable – soybean	Digital irrigation management/DSS (soil-moisture sensors, weather station, automated pump control) on a pivot system	In-depth
9	North Macedonia (RAMAS LL)	Viticulture – vineyard	RAMAS advisory platform (FMIS) + weather station	In-depth
10	Spain (Almería Agroecology LL)	Protected horticulture – greenhouse	Integrated platform: automated farming practices, sensors, monitoring app	Online (6 respondents)
11	France (LIT Ouesterel LL)	Livestock – pig	PigLink digital interoperability / decision-support platform	Online (1 respondent)
12	Latvia (Local beef cattle farming LL)	Livestock – cattle, sheep, beef	Cameras, sensors, surveillance & counting systems, DSS	Online (5 respondents)
13	Estonia (Grassland management LL)	Grassland management	Drone mapping / satellite maps, sensors, software	Online (3 respondents)

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N.	Living Lab / Country	Production system	Digital technology assessed	Data type
14	France (Occitanum Open Lab Sheep)	Livestock – dairy sheep	Electronic milk meters (individual recording) + automatic feeder	Digital-scenario DCF only
15	Germany (Agri-Digital Bildung)	Knowledge transfer / arable	Vocational-education format promoting precision & digital technologies	No economic data
16	Ireland (Cloughjordan Food Hub)	Local food / short food supply chains	Open-source, producer-owned digital marketplace (Open Food Network)	No economic data
17	Italy (Organic Table Grapes LL)	Viticulture – organic table grapes	Precision irrigation: weather station + sensors + DSS)	No economic data
18	Poland (APPETIT LL)	Short food supply chains	IT-enabled virtual + physical local-food marketplace	No economic data
19	Scotland (Hutton LL)	Small/mixed farms & crofters	Knowledge-exchange platform + range of digital tools (social media, QR, VR, sensors) virtual demonstrations	No economic data
20.	France (Occitanum Viti)	Viticulture	Digital technology to be tested was changed during CODECS	No economic data

The related datasets comprising all the Economic C&B reports produced by ELGO-DEMETRA and the LL as part can be visualized in the Zenodo Repository : 10.5281/zenodo.21649169

4.5 Preliminary findings of the economic analysis

The economic analysis is still ongoing, and the results presented here are preliminary. They are shared at this stage to give an early sense of direction. The complete analysis, based on finalised set of case studies, will be presented in the final deliverable.

A common result is that, in all nine in-depth case studies, the adoption of the digital technology proved economically viable under specific conditions and assumptions. The partial budget produced a positive net annual benefit and the NPV was positive at the base discount rate of 5%. This is a notable finding, but it must be read together with two qualifications: several cases are viable only above a minimum farm size, and the Living Labs analysed are early adopters and demonstration farms, not representative of European agriculture as a whole.

Reductions in labour requirements and workload were among the most consistent and important benefits observed, and input savings – plant protection, fertiliser, water and energy – were the second major path of benefit, in several cases the dominant one. Notably, several cases (Belgium, Czech Republic, Greece, Hungary, Slovenia) were shown to be profitable without assuming any yield increase at all; the benefits came entirely from cost savings.

The single most important cross-cutting finding is that the economic viability of on-farm digitalisation depends critically on farm size and the intensity of use of the technology. This has a clear practical implication: the same technology can be a sound investment on one farm and a loss-making one on a smaller one. It also points to two

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important adoption pathways for small farms – outsourcing/service provision and cooperative or joint investment – which allow small holdings to reach the necessary scale without bearing the full fixed cost individually.

The online-only Living Labs and those without collected economic data broaden the picture but remain qualitative and based on a small number of respondents, so they complement rather than confirm the in-depth results.

4.6 Conclusions

The main significance of this work is that it rests on empirical, farm-level data on the economics of digital-technology adoption, data that are genuinely rare. Most existing evidence on the benefits of agricultural digitalisation is based on expectations, perceptions, experimental trials or manufacturers' claims rather than on the actual, realised costs and benefits recorded on farms. By collecting technical and economic data before and after adoption from real adopters and demonstration farms across thirteen Living Labs (complemented by a further group of Living Labs for which only anticipated costs and benefits are so far available) and by applying a consistent partial-budget and NPV framework, CODECS provides a rare, comparable, evidence-based assessment of whether and under what conditions on-farm digitalisation is viable. The consistent finding that all nine in-depth cases were economically viable at a 5% discount rate is encouraging, the equally consistent finding that viability depends on farm size, intensity of use and the specific cost items affected is what makes the evidence genuinely useful for decision-making.

However, the results must be interpreted with a clear understanding of their limitations:

- **Case-study nature.** The analyses are case studies of specific farms, technologies and contexts. They are not statistically representative of European agriculture, and the results cannot be generalised without further analysis.
- **Early adopters and demonstration farms.** The farms analysed are, by design, early adopters or demonstration sites, often supported within CODECS (in several cases the technology was provided at little or no cost to the farmer), so some real-world costs are under-represented.
- **Data gaps and assumptions.** Several analyses relied on assumptions and secondary data (wages, prices, interest rates) or lacked a genuine "before" reference, and some benefits (yield, quality, risk reduction) were deliberately excluded from the base case to avoid over-statement. Where reference and digital scenarios came from different years (Italy), market effects are entangled with technology effects.
- **Small samples in the online survey.** The online-only LLs rest on very few respondents (one in the French case), so their findings are indicative only.
- **Technology and regulatory maturity.** Some benefits are currently constrained by the wider ecosystem, the absence of drone-specific plant-protection products (Greece) or of legal authorisation for drone spraying (Europe) and may change as that ecosystem matures.

Notwithstanding these limitations, the results are highly useful for several audiences. For farmers and advisors, they provide a realistic, thorough picture of the costs and benefits of specific technologies, the conditions (especially farm size) under which they pay off, and the adoption pathways available to smaller farms (outsourcing, cooperation). For the CODECS assessment framework, they supply the economic component that will feed into the multicriteria and trade-off analysis of Task 4.6, and the parameters needed to build web-based decision tools. For policy makers, they highlight where public support is most effective (offsetting fixed investment costs, enabling access for small farms, removing regulatory barriers) and caution against undifferentiated support. And for the wider evidence base, they contribute rare empirical data points to a literature dominated by expectations rather than realised outcomes.

4.7 Forthcoming steps

- M46 – M48: Synthesis of the Economic Costs and Benefits findings at the scale of CODECS use-cases
- M46 – M48: Communication set for each LL (Practice abstract)
- M48: Policy Brief and final deliverable

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5 Social/human-centred costs and benefits assessment of farm digitalisation

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5.1 Introduction

This chapter related to the Task T4.5 of WP4 investigates the **social/human-centred costs and benefits** of farm digitalisation – defined in Section 5.2 as *the influence of digital tools on farmers and all people engaged in farm work at the farm level, with a focus on intangible effects*. It addresses a gap in a literature dominated by economic and macro/meso analyses by examining micro-level human transformations in context. The objectives are to deepen understanding of how digital technologies reshape farmers' practices and well-being, and to generate practical insights for farmers and decision-makers to support responsible, inclusive digitalisation.

Methodologically, the study follows a two-step qualitative design. A multidisciplinary workshop (March 2023) first established a common framework across three key components – people, work, and social interaction – and clustered "unitary indicators" into five families: Health & Well-being, Skills & Knowledge, Quality of Work, Time, and Communities & Networks. Crucially, the workshop outputs directly informed the themes used in the second-phase semi-structured interviews. These interviews were conducted across CODECS Living Labs with both Digitalised and Digitalising farms, eliciting realised and anticipated human changes within diverse socio-economic and cultural settings. Phrase-level content analysis, undertaken by independent teams using MAXQDA and NVivo, enables systematic coding and cross-checking to ensure reliable, balanced results.

By February 2025, we received 24 interviews from 14 Living Labs (crop, livestock and mixed systems; decision-support, input-monitoring and marketplace tools) had been collected. Data analysis (M24–M32) synthesises empirical evidence to elucidate benefits and associated cost, thereby generating insights that inform advisory practice and policy to maximise positive human outcomes while mitigating adverse consequences of the digital transition.

5.2 Human-centred Costs and Benefits of using digital technologies at farm level

Research evaluating digital technologies in agriculture has primarily focused on their economic dimensions. Scholars have recently emphasised the need for further research that not only prioritises profit generation but also addresses the social aspects of digitalisation. This includes adopting responsible innovation approaches (Roy, 2021; Bronson, 2019; Bellon-Maurel et al., 2022) and supporting skills development to enable more inclusive and sustainable digitalisation processes for farmers and other rural actors (Cowie et al., 2020).

The study of the social dimension of sustainability has gained importance in agriculture due to pressing issues such as the decline in the number of farmers and the depopulation of rural areas. In general, it is acknowledged that social sustainability encompasses aspects from the farmer's perspective as well as those relating to the wider social system surrounding the farm. Although a universally accepted definition of the social dimension of sustainability in the agricultural context is still lacking (Ait, 2018), research focusing on the intersection of agriculture and digitalisation can be classified into three scales of observation, with studies unevenly distributed across them. Current knowledge predominantly concentrates on the macro level, examining impacts on society as a whole (Bronson, 2019), and on the meso level, referring to implications of digitalisation at a regional scale among farms (Carolan, 2015). By contrast, research at the micro level – focusing on farmers and farm households – remains a nascent field (Klerkx et al., 2019; Rose et al., 2021; Van der Burg et al., 2019). Consequently, scholars have called for more research on how digital technologies affect humans at the farm level, in order to avoid creating additional social problems (Rose et al., 2021). Such research is also needed to develop more inclusive and equitable approaches to digitalisation in agriculture,

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ones that take into account a greater diversity of human values and encompass all types and scales of farms (Bronson, 2019)..

Although research into the human impacts of farm digitalisation is increasingly active, important gaps remain. First, existing studies focus primarily on robotics and precision agriculture tools (Vik et al., 2019; Townsend & Noble, 2022). In addition, research is fragmented across a range of issues related to human values, including health (Goutille et al., 2023; Sparrow & Howard, 2020), skills and knowledge (Legun et al., 2022; Klerkx et al., 2019), and work organisation (Hidalgo et al., 2024; Prause, 2021; Rose et al., 2021). Furthermore, defining and analysing the social dimension of sustainability is challenging due to its inherently subjective elements, such as user health and perceptions, which influence outcomes at the micro level (Ait, 2018). The complex interconnections created by digital technologies – among people, technologies, and institutions – further complicate attempts to identify and interpret the resulting social changes (Benbya et al., 2020).

It is essential to recognise that digital technologies should not be considered universal, as their impact is shaped by socio-economic, cultural, and political factors in different contexts (Klerkx & Rose, 2020). This complexity makes studying the social and human aspects of digital technology adoption and use particularly challenging. By understanding how digital technologies influence farmers and their activities, we can generate valuable knowledge to share with other farmers, while also helping to reduce resistance to new technologies in some cases. Policymakers can draw on these insights to design and support policies that mitigate negative consequences and strengthen positive social and human outcomes arising from the adoption and use of digital technologies at the farm level.

5.3 Design research

The objective is to evaluate the social-human costs and benefits of digitalisation at the farm level, mainly, by identifying and enhancing the understanding of the adoption and use of digital technologies by farmers.

Based on the introduction and the objective, the task will seek to address the following research question: **How does the adoption and use of digital technologies affect farmers and farmers' practices?**

To address the research question concerning human costs and benefits, T4.5 researchers conducted a qualitative study among farmers identified in the CODECS Living Labs. This encompassed both positive and negative human changes affecting farmers and their agricultural practices. Social-human aspects included exploring the effects of these technologies on farmers' well-being, social interactions, labour, and overall quality of life within their specific socio-economic and cultural contexts. By collecting qualitative data, the researchers aimed to gain a comprehensive understanding of the social-human implications of using and adopting digital technologies at the farm level.

A two-step approach was implemented in this task. First, we organised a workshop that brought together T4.5 researchers from various disciplines to explore the potential transformations - both positive benefits and negative costs - that digitalisation may bring to farmers and farm operations. The insights gained from this workshop served as the foundation for developing semi-structured interviews for data collection among farmers in the various Living Labs.

5.3.1 Workshop on human costs and benefits resulting from farm digitalisation

We conducted the workshop in March 2023, following the recommendation of Rose et al. (2023) to explore multidisciplinary fields that consider farm-level changes and their sustainable outcomes, with human-centred aspects at the core of discussion. The workshop aimed to identify and organise the human-centred costs and benefits of digitalisation at the farm level.

First, it was agreed to adopt the concept of "human-centred costs and benefits". The "human" aspect highlights "soft impacts" in the literature, often qualitative and focused on the human dimension (Van der Burg et al., 2019). The "costs and benefits" terminology reflects the dual nature of digitalisation, covering both positive and negative impacts (Murphy & Simon, 2004).

Second, participants discussed and, in line with previous research, agreed that digitalisation affects three "key human components" on farms: (i) farmers, employees, or family members engaged in agricultural activities (Rose

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et al., 2021); (ii) work, the tasks performed using digital technologies (Klerkx et al., 2019; Carolan, 2018); and (iii) the organisation of the production system (Klerkx et al., 2019; Vik et al., 2019).

In the second part of the workshop, participants considered how digitalisation might influence these components to define "unitary indicators" of human-centred costs and benefits. The interactive format encouraged iterative discussions and refinements. Indicators for (i) farmers, defined as anyone engaged on farms, including employees and family members, were grouped into Health & Wellbeing and Skills & Knowledge. Indicators for (ii) work were clustered into Quality of Work and Time. For (iii) the organisation of the production system, only one family of indicators emerged: Communities & Networks.

The workshop proved to be an effective in addressing the challenges outlined in the literature, particularly the fragmented research on human values and the difficulty of defining the social dimension of sustainability, further complicated by dominant subjective factors. These factors, in turn, contribute to the complexity of identifying social changes driven by digital technologies (Benbya et al. 2020). The workshop therefore provided a foundation for defining, discussing, and structuring potential human-centred costs and benefits in digital agriculture.

Below, we present our qualitative method for data collection and analysis, providing a description of expected human-centred cost and benefits, inclusion and exclusion criteria for farmers, the semi-structured interview questions, and some advice for interviewers.

Figure 11 shows some examples found in France of human-centred costs and benefits of digitalisation for five groups, organised into three main human components.

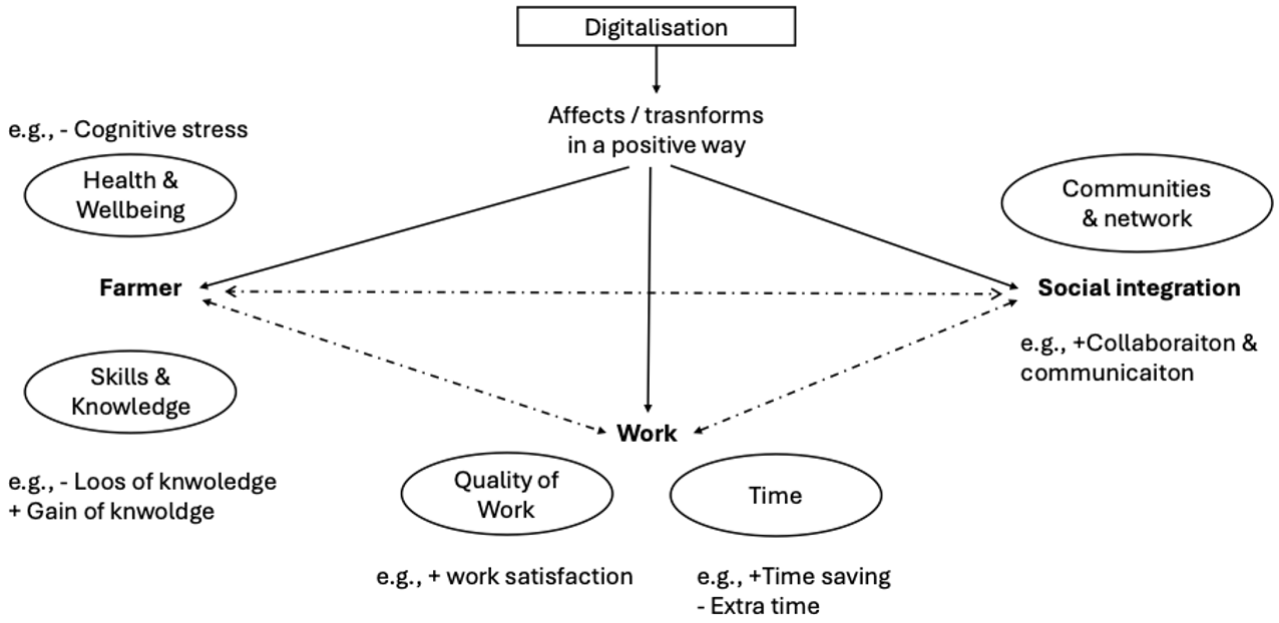

Figure 11: Human-centred Cost and Benefits digitalisation at the farm level

5.3.2 Semi-structured interviews

We chose to use a qualitative method to deeply understand the experiences and perspectives of farmers regarding the human-centred costs and benefits of adopting and using digital technologies in various situations, including living labs, different countries, farm conditions, and with different technologies.

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Considering our research question, a qualitative approach is suitable for exploring a topic that has not been extensively studied in the literature and lacks strong theories (Trauth, 2001). Moreover, it acknowledges that the results, of adopting and using digital technologies, may vary depending on the specific context.

Data for this stage of research are collected through semi-structured interviews, enabling farmers from Living Labs to freely share their experiences and perspectives on adopting and using digital technologies (Furneaux & Wade, 2011). Additionally, this approach allows to address the potential human-centred costs and benefits discussed, here before presented, by the members of T4.5 in terms of farmers well-being, work, and the social integration.

5.3.3 Data collected

Table 5 summarises the collected data up to September 2025. The table provides an overview of two levels of digitalisation – Digitalised and Digitalising – where data was collected.

- **Digitalised Farms:** Involve 6 Living Labs, 9 interviews, and 37.106 words transcribed. The types of farms participating in this group include crop, livestock, and mixed operations. The digital technologies used are **Decision Support Tools, Monitoring Input Management**, and **Marketplaces**, aimed at improving **decision-making and sustainability.**
- **Digitalising Farms**: Include 11 Living Labs, 15 interviews, and 53.605 words transcribed. Similar to digitalised farms, these also span crop, livestock, and mixed types. The technologies focus on Monitoring Input Management and Marketplaces, with additional purposes of improving decision-making, the local food economy, digital literacy, and sustainability.

Table 5 Description of the collected data in T4.5 (M18 – M36)

Digitalisation Level	Living Lab country	# interviews	# words transcriptions	Type of farms	Technology cluster	Technology purpose
Digitalised	Ireland, Slovenia, Germany, Hungary, France & Estonia	9	37.106	Crops, livestock and mixed	IMT and ICT*	Support decision-making and sustainability
Digitalising	Poland, Latvia Serbia, Scotland, Belgium, Spain, France, Greece Cech Republic, Slovakia & North Macedonia	15	53.605	Crops, livestock and mixed	IMT and ICT	Support decision-making, support local food economy, enhance digital literacy and sustainability

*IMT: Input Management Technologies; ICT: Information Communication Technology

5.3.4 Content analysis of the interviews

All interviews were transcribed, translated into English, and analysed by a separate team to ensure consistency. We applied a hybrid thematic analysis (Dueñas-Ocampo et al., 2024) that combined deductive strategies (Crabtree & Miller, 1999) with inductive ones (Boyatzis, 1998). This approach sought to identify recurring patterns and core themes (Daly et al., 1997; Fereday & Muir-Cochrane, 2006), using a template of themes developed in a research workshop while remaining open to new categories.

The coding protocol, adapted from Deng et al. (2016), followed four steps: (i) three two-person coding teams each analysed 7–8 interviews, with one researcher embedded across all teams to ensure consistency; (ii) researchers independently coded their assigned interviews; (iii) team members compared outputs and resolved discrepancies;

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and (iv) a consensus meeting integrated results into a final coding framework. NVivo and MAXQDA supported coding, while memos were organised in Excel and refined through team discussions until agreement was reached on final category definitions and interpretations.

5.4 Results

This work has been published in 2026 in the *Journal of Rural Studies* under the title "**Exploring farmer's lived social costs and benefits of digitalisation."** (Florez et al. 2026) 10.1016/j.jrurstud.2026.104252

Hereafter, the overview of findings.

5.4.1 Overview of findings

The 24 semi-structured interviews conducted across 16 European countries confirmed and extended the three-dimensional analytical framework (farmer well-being, work organisation, social interaction) developed during the interdisciplinary workshop. Findings show that digitalisation produces **simultaneous and interdependent social costs and benefits**, rather than a uniform positive or negative trajectory. This duality was consistent across both technology clusters (Precision Agriculture and ICT-based platforms).

Benefits identified include: **improved farmer well-being through better working conditions**, through reduced physical effort and better work–life balance; **expressing farming identity and values through digitalisation**; **better access to expertise and informed decision-making**. At work level: **enhanced risk management and harvest safeguarding**, **job satisfaction through ethical and sustainable farm management**, **socially inclusive market participation**, and **creating time for life beyond work**. Socially: **strengthening farmers' connections** and **attracting the next generation through innovation and modern image**.

Social costs include: **mental toll of digitalisation**, **erosion of farmer identity and autonomy**, **financial and hidden costs affecting health and well-being**, and **continuous need to upgrade skills and knowledge**. At work level: **operational burdens and work complexity** and **workforce reduction and workplace tensions**. Overall, digitalisation is socially ambivalent – its effects depend on how technologies fit farmers' values, skills, resources, and support systems.

The following tables (Table 6 and Table 7) present the general social costs and benefits of farm digitalisation identified across all Living Labs in the CODECS study.

Table 6 Social costs of farm digitalisation (CODECS general findings).

Themes	Categories	Social Costs	Description
Farmer	**Health and Well-being**	Mental toll of digitalisation	Managing digital tools adds stress, from cybersecurity concerns to frustrations with interoperability and missing key parameters. The constant pressure to upgrade and stay connected contributes to fatigue, making it harder to disconnect from work
		Erosion of farmer identity and autonomy	As decision-making becomes increasingly data-driven, farmers may feel disconnected from their traditional roles. Dependence on technology providers for maintenance and analysis reduces autonomy, while automated recommendations cannot fully replace intuition and experience

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Themes	Categories	Social Costs	Description
		Financial and hidden costs affecting health and well-being*	Digitalisation involves high initial costs, hidden fees, and ongoing expenses. Adapting to rapid technological changes, while managing payment delays and non-refundable services, adds financial complexity that can contribute to increased stress, frustration, and overall negative impacts on farmers' well-being
	Skills and Knowledge	Continuous need to upgrade skills and knowledge*	Digitalisation demands new competencies that vary among farmers, requiring ongoing learning and support. Generational gaps in digital literacy make adaptation uneven, and many technologies remain underutilised due to a lack of training
Work	**Quality of Work**	Operational burdens and work complexity	Digital systems can lead to workflow disruptions, maintenance expenses, and delays in farm operations. Unforeseen technical issues may reduce efficiency instead of improving it, creating additional burdens
		Workforce reduction and workplace tensions	The shift to digital tools affects labour structures, reducing job opportunities and creating new workplace tensions. Differences in digital skills between generations impact work management and even leisure time distribution
Social Interaction	**Communities and Networks**	NA	NA

Table 7 Social benefits of farm digitalisation (CODECS general findings).

Themes	Categories	Social Benefits	Description
Farmer	**Health and Well-being**	Improve farmer well-being through better working conditions	Digital tools contribute to better quality of life by reducing physical effort, improving work-life balance, and enhancing overall well-being. Automation and optimised workflows lead to increased job satisfaction for both farmers and workers
		Expressing farming identity and values through digitalisation	Farming is increasingly experienced as a knowledge-driven and purposeful profession, where individuals actively shape how their work is understood and valued. Farmers emphasise authenticity, local roots, and production practices to express who they are and what they stand for
	Skills and Knowledge	Better access to expertise and informed decision-making*	Digitalisation democratises knowledge by improving access to data and insights. Farmers make more informed decisions, increasing confidence in their management strategies and optimising farm performance

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Themes	Categories	Social Benefits	Description
Work	**Quality of Work**	Enhance risk management and harvests safeguarding*	Farmers move from reacting to uncertainty to anticipating it, gaining a stronger sense of control over their work. This reduces stress and builds confidence in managing increasingly unpredictable conditions, reinforcing everyday resilience
		Job satisfaction through ethical and sustainable farm management	Digitalisation encourages more environmentally responsible practices by supporting informed decisions around fertiliser use, soil care, and resource management. These improvements contribute to a stronger sense of responsibility and satisfaction in sustainable farming
		Socially inclusive market participation	Digital tools support farmers in gaining greater agency by engaging more directly with their markets, strengthening control over how they sell and connect with others. This fosters autonomy, recognition, and more balanced relationships, reinforcing both economic resilience and social inclusion
		Creating Time for Life Beyond Work	Better organisation of daily activities enables farmers to free up time for themselves, their families, and community life. This renewed balance reduces the feeling of being constantly tied to work and supports well-being, personal fulfilment, and social engagement
Social Interaction	**Communities and Networks**	Strengthening Farmers' Connections	Digital tools facilitate stronger relationships with customers, stakeholders, and advisors. Improved communication and collaboration enhance marketing strategies and build trust within the agricultural community
		Attracting the next generation through Innovation and modern Image	Modernising agriculture with digital tools helps attract younger generations by reshaping the image of the sector. Greater flexibility, emerging roles, and a stronger sense of purpose contribute to making farming more appealing as a meaningful and contemporary profession

Digital tools, Input Management Technologies (IMT) and Information Communication Technologies (ICT), bring advantages such as better decision making, stronger risk management, greater social integration and attraction of new generations. At the same time, farmers face challenges linked to mental wellbeing, identity, workplace complexity, the need for continual upskilling, and generational gaps in digital literacy that reshaped relations at work and at home. These findings highlight how efficiency and modernisation are closely tied to emotional strain and shifting social dynamics in agricultural work.

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5.5 Discussion

This study examined the social costs and benefits of digitalisation at farm level, drawing on 24 interviews with farmers participating in Living Labs across Europe. The findings are discussed below across the three dimensions identified in the analytical framework – farmer well-being, work organisation, and social interaction – followed by the cross-cutting patterns and limitations that emerged from the analysis.

- **Farmer well-being and the autonomy paradox**

The interviews show that digitalisation does not simply take away or add to farmer autonomy. It changes its form. Farmers described greater control over decision-making once they had access to farm-level data, yet many became more dependent on external providers for maintenance, software updates, and interpretation of that same data. This mirrors earlier socio-technical accounts of digital agriculture (Bronson and Knezevic, 2016; Klerkx et al., 2019). It suggests autonomy in this context is not something an individual farmer simply has more or less of, but something distributed across the wider technical arrangement they operate within.

- **Stress and frustration are not the same thing**

Two distinct emotional responses came through in the data, and the distinction matters for how CODECS frames its recommendations. Stress came from sustained exposure to complex systems and constant data flow, and farmers dealing with this tended to need training, time, and other coping resources. Frustration came from a different place: money spent on tools that underperformed, refunds that never arrived, support that wasn't there when needed. Addressing frustration requires better usability and service quality, and some form of shared financial risk between farmers and providers. Lumping both under a single "technostress" label would obscure this and likely lead to the wrong kind of support being offered.

- **Work organisation and unequal digital capital**

Automation reduced manual workload on the farms interviewed, but it also reshaped who has authority within the farm. Family members or employees with stronger digital skills tended to gain influence over tasks and decisions that others could no longer easily follow. This is less about whether a technology was adopted and more about unequal digital capital – access, skill, and confidence – echoing Ragnedda (2018) and the idea of digital restructuring of agricultural labour put forward by Devlin and Bleakley (2021).

- **Social interaction and inclusion**

Digital technologies seemed to strengthen farmers' connections to people outside their immediate circle – advisors, buyers, other farmers in different regions – what the literature calls bridging social capital. At the same time, some farmers pointed to a weakening of the closer, place-based relationships that make up bonding social capital, in line with Townsend et al. (2016). The two effects don't cancel each other out; they run in parallel. This points to a practical conclusion: digital strategies should be built to sit alongside existing local networks rather than to replace them.

- **A cross-cutting pattern**

Taken together, the same technology produced very different outcomes across interviews depending on two conditions: whether the financial cost was manageable and transparent, and whether adequate technical support and training were actually available. These two conditions look like the main levers through which the overall social outcome of digitalisation could be shifted in a more positive direction – a point with direct relevance for CODECS' policy and advisory work.

- **Limitations**

Because participants were drawn from Living Labs, the sample likely skews toward farmers already comfortable with digital tools, so these findings may understate the difficulties faced by less digitally engaged farmers. The study also spans many countries without being able to isolate national institutional or policy differences; this would need larger, within-country samples in future CODECS work.

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5.6 LL Social C&B reports

For each LL, a report has been provided, to support discussions among stakeholders on the specific topic of social C&B. The related datasets produced by INRAE and the LL as part can be visualized in the Zenodo Repository : **10.5281/zenodo.21649560**

5.7 Upcoming steps

- Contribution to the practice abstracts
- Synthesis report on Social C&B in the final deliverable
- Valorisation of the data collected (conference and articles)

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Funded by the European Union

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6 Multi-Criteria Assessment of costs and benefits

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6.1 Objectives and achievements

In T4.6, the objective is to carry out an integrated assessment of economic, environmental, social benefits and costs of farm digitalisation, to identifying trade-offs and system dynamics, through a Multi-Criteria Assessment methodology.

To achieve it, the first step was to consolidate shared principles on criteria selection, actor engagement and the integration of environmental, economic, social and enabling-condition dimensions. Although not formally reported under T4.6 at that stage, these preliminary dialogues created a common methodological ground and clarified the strategic role of a Multi-Criteria Assessment in synthesising the diverse C&B analyses developed in Tasks 4.2-4.5 and translating them into Living Lab-centred, policy-relevant insights.

Task 4.6 progressed from conceptual design to a fully operational Multi-Criteria Assessment (MCA) framework tailored to the diversity of CODECS Living Labs. Building on prior methodological work, the team created a structured approach capable of evaluating multiple digital technologies across heterogeneous farming systems, stakeholder groups and digital maturity levels.

A major achievement was translating the conceptual background into a practical, standardised MCA methodology. This included defining the decision problem, identifying key actors, structuring the alternatives (technologies/use cases), and establishing five evaluation domains (economic, environmental, social, enabling conditions, data/knowledge). To ensure comparability with other project activities, three digitalisation scenarios (S0–S2) were adopted. The scoring system used a symmetric -3 to +3 scale to capture both positive and negative impacts, complemented by a certainty score (1-5). Each score required a textual rationale, ensuring transparency and contextual interpretation.

Operational tools were developed, including detailed MCA Workshop Guidelines, methodological presentations, and 26 technology factsheets. Extensive coordination across Task 4.6, WP4, and WP2 ensured coherence in criteria, data expectations and integration with other assessment tools. Preparations culminated in a pilot MCA workshop at the Ljubljana General Assembly, involving all 18 Living Lab coordinators. The exercise generated rich qualitative insights and validated the methodological approach, although time constraints limited full scoring for some groups.

The workshop also highlighted practical challenges, notably the need for more time to achieve consensus on scores and to address system-level criteria. These findings informed refinements to the MCA Guidelines and the planning of follow-up LL-level sessions. The next Reporting Period will include targeted interviews and mini-workshops to complete scoring, improve rationale quality and secure balanced datasets across technologies and scenarios.

Task 4.6 had established a robust, tested, and actor-centred MCA framework and agreed on a roadmap for its LL-by-LL implementation, comparative analysis and integration into the WP4 synthesis and Policy Brief 12. The principal achievement at M46 is the successful creation of such a framework, fully aligned with the structure and objectives of CODECS. The Task team has transformed conceptual principles and previous project-specific experiences into a methodology capable of comparing the expected impacts of digital technologies across diverse agricultural systems.

The complete list of the achievements at M46 is available hereinafter:

- completion of the MCA methodology, clearly defined and shared across partners, including criteria selection, scenarios, scoring logic, actor roles, aggregation methods (AHP, TOPSIS) and interpretation procedures,
- elaboration of MCA Workshop Guidelines, providing a ready-to-use toolkit for LL-level participatory assessment, including templates, instructions, and guiding questions,

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- delivering of twenty-six technology factsheets, ensuring comparability of alternatives across LLs and supporting participants' understanding during the evaluation,
- production of a first exploratory dataset generated during the Ljubljana workshop, offering initial insights into perceived impacts, key trade-offs and enabling conditions, while also highlighting where further data collection is required,
- strong cross-WP alignment, particularly with WP2 (VARI tools) and WP7 (Multi-Criteria Assessment tool), ensuring that Task 4.6 contributes coherently to the overall evaluation architecture of CODECS.

Overall, Task 4.6 has reached a stage of methodological readiness: the approach is designed, tested, refined and fully accepted by the Living Lab coordinators who will implement it.

6.2 Upcoming tasks

- Comparative analysis across clusters
- Contribution to the synthesis report
- Scientific valorisation
- Contribution to the policy brief

7 Concluding remarks

This deliverable brings together substantial progress across the five tasks of WP4, moving from methodology and early findings towards consolidated, empirically grounded results on the costs and benefits of farm digitalisation. Perceptions have matured from broad expectations to concrete, condition-dependent assessments; the environmental analysis shows measurable but often modest efficiency gains; the economic analysis confirms viability under specific conditions, chiefly farm size; and the social analysis reveals a consistent duality of costs and benefits across well-being, work organisation and social interaction. Together, these findings point to a shared conclusion across dimensions: the outcome of digitalisation depends less on the technology itself than on the conditions surrounding its adoption – scale, cost transparency, technical support and governance.

The remaining work for the coming period is to bring these dimensions together. The multicriteria framework developed in T4.6 provides the operational basis for this integration, and its application across the Living Labs, combined with the finalisation of the economic, environmental and social analyses still underway, will form the core of the final synthesis report at M48. That report will offer farmers, advisors and policymakers a single, evidence-based account of the trade-offs and synergies of farm digitalisation across all three sustainability dimensions.

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