Synthesis report on Environmental, Economic, and Social C&B of farm digitalisation, draft M36

30 SEPTEMBER 2025

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DOI: 10.5281/zenodo.17235873

Status: submitted draft not yet approved by the EC

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SYNTHESIS REPORT ON ENVIRONMENTAL, ECONOMIC, AND SOCIAL C&B OF FARM DIGITALIZATION, DRAFT M36

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	D4-2_C&B_Farm_digitalisation_DraftM36_v2_30032026.doc
Status	Final
Dissemination level	Public
Date of creation	29.09.2025
Keywords	Digital agriculture, Farm digitalisation, Environmental, Economic, Social-human, Costs and Benefits, Impacts, Perceptions
Authors	Alexia Gobrecht, Mauro Florez, Veronique Bellon-Maurel, (INRAE) Constantine Ilioupoulos, Irini Theodorakopoulou, Alexandra Sintori, Thomas Giotis (ELGO-DIMITRA), Beatriz Herrera (UHOH), Leanne Townsend, Niamh Mahon, Tim Pittaway (HUTTON), Maija Usca, Emils Killis (BSC), Karine Gauche (Institut Agro)
Reviewers	
Version n.	1.0
Following updates	DEL4.3_C&B_Farm_digitalisation_DraftM46(M46), 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 digitalization, 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
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History of changes			
Version	**Date**	**Changes**	**Authors(s)**
0.1	03.06.2025	First draft	Alexia Gobrecht (INRAE)
0.2	25.08.2025	Second draft	Task Leaders
0.3	28.09.2025	Final Document review	Alexia Gobrecht (INRAE)
1.0	30.09.2025	First version approved and released	
2.0	30.03.2026	Revised version	Alexia Gobrecht (INRAE)

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Executive summary

This deliverable synthetises progress made in WP4 of the CODECS project during the first 36 months. It focuses on the **Costs and benefits analysis (C&B) of farm digitalisation accross economic, environmental and social dimensions.**

Three objectives guide this work: (i) capturing stakeholder's perceptions of digitalisation (T4.3), (ii) assessing C&B through dedicated methodologies for each sustainability dimension (T4.3, T4.4 and T4.5) and (III) preparing a multicriteria framework to explore trade-off and synergies (T4.6).

Significant advances have been achieved. Perceptions analysis across the Living Labs reveals both strong expectations for efficiency, environmental improvements, and new market opportunities, alongside concerns over trust, dependency, skills, and governance. First environmental life cycle assessments provide evidence of efficiency gains but also highlight methodological challenges and potential trade-offs. Economic analyses demonstrate both costs of investment and opportunities for improved profitability, while social/human-centered assessments document impacts on farmers' well-being, work organisation, and interactions.

Methodologies have been adapted to the diverse contexts of the LL, with guidelines and training provided to Living Lab coordinators. Data collection and validation are still ongoing, forming a robust foundation for integrated analysis. Crucially, WP4 also emphasises returning results to the Living Labs and their stakeholders, ensuring that farmers, advisors, and local actors benefit directly from the knowledge generated. This two-way exchange strengthens the relevance of the analyses, fosters trust and supports real-world decision-making in diverse farming contexts.

Looking ahead, WP4 will continue the economic, environmental, and social dimensions analysis, while also working towards a more holistic perspective. The aim is to develop practical ways of linking insights across dimensions to highlight trade-offs and synergies. This balanced approach will provide farmers, policymakers, and other stakeholders with evidence that is both rigorous in each pillar and meaningful when considered together, supporting more informed and context-sensitive decisions.

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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.

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 Lab 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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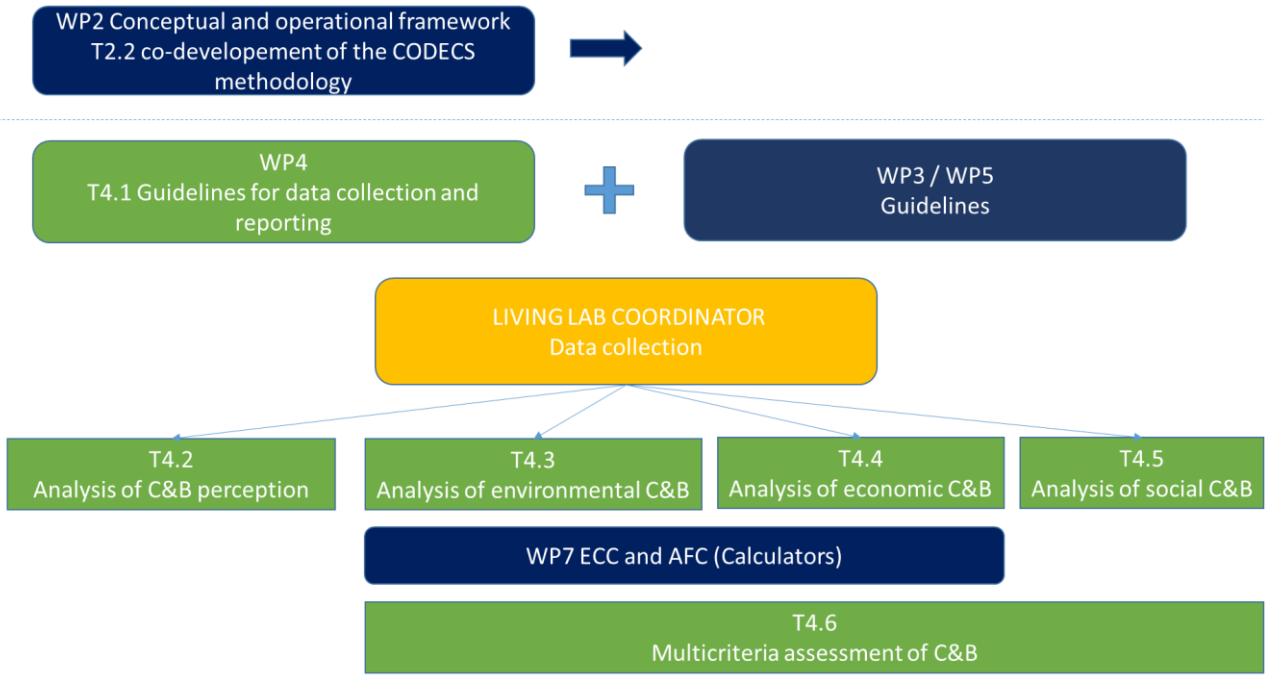

Figure 1: Articulation of WP 4 tasks

1.3 Advances of WP4 (M24 - M36)

As said above, methodologies used in WP4 were at different stages: some were already well established, others had to be adapted or even built from scratch. In addition, the dynamics of data collection were heterogeneous regarding the criterion to be assessed. Data collection for Perception of Cost and benefits (T4.2) were carried out during annual Living Lab Workshops in 2023, whereas data collection for assessment of digitalisation C&B is carried out in each living lab, starting with data related to the social cost and benefits (Summer & Autumn 2024), and finally Environmental and Economic data during spring & summer 2025. This explains a heterogeneous advancement of the results.

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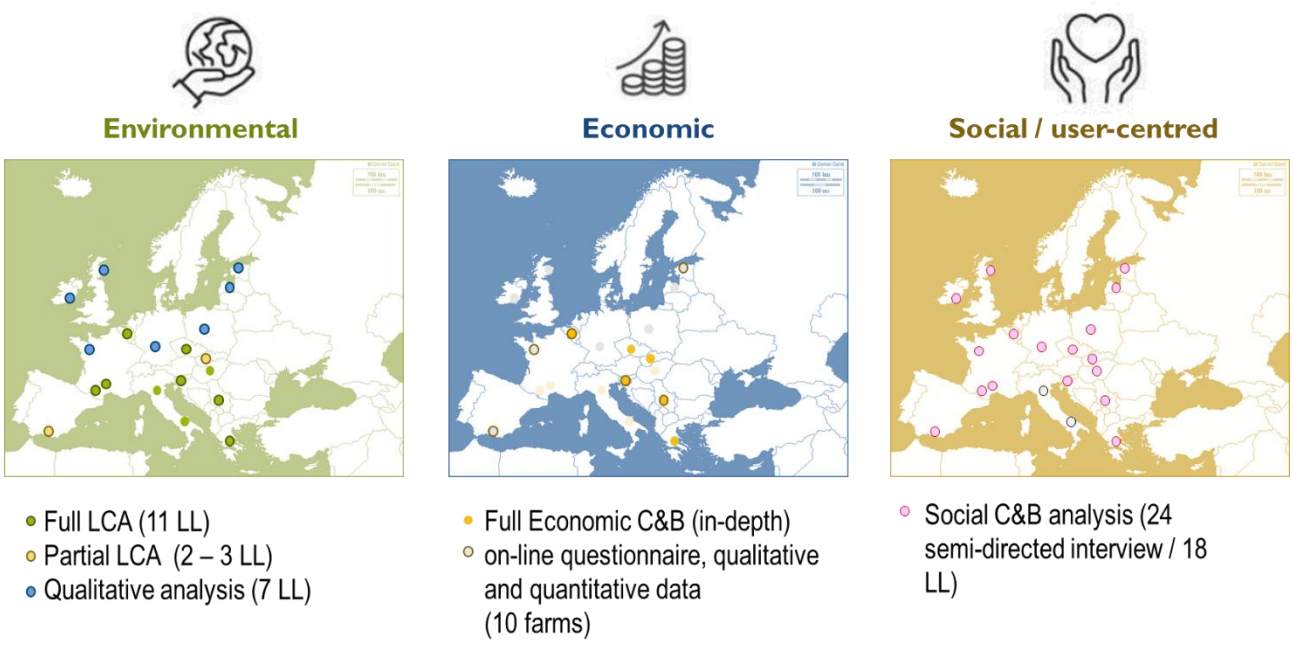

Figure 2 Data collected in the different LL for each sustainability dimension

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

In the following sections, we will introduce the methodologies and the updated outputs of the different tasks.

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

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

2.1 Introduction

The digitalisation of agriculture has emerged as one of the most significant drivers of transformation in European agri-food systems over the last decade. Digital technologies such as precision farming tools, remote sensing, unmanned aerial vehicles (UAVs), decision-support platforms, and farm management information systems promise to enhance farm productivity, optimise input use, support sustainability goals, and improve resilience to climate and market volatility. However, their adoption is not uniform across Europe and raises complex questions regarding costs, benefits, governance, and the distribution of risks and opportunities.

In the context of the CODECS project, WP4 investigates the environmental, economic, and social costs and benefits (C&B) of farm digitalisation. As part of this, we carried out a systematic mapping of stakeholder perceptions of digitalisation in 18 Living Labs (LLs) distributed across Europe. These LLs cover a wide diversity of farming systems (arable, livestock, horticulture, viticulture, mixed farming) and socio-economic contexts (Northern, Central, Southern, and Eastern Europe). By mobilising participatory methodologies, this task aimed to capture how farmers, advisors, policymakers, technology providers, and other stakeholders perceive the short- and long-term implications of digitalisation.

The first phase of this work was conducted between M18–M24 (Oct. 2023 – Mar. 2024) through focus groups. Its results were reported in Deliverable 4.1 (pp. 15–50) and further consolidated in the peer-reviewed article “Perceptions of costs and benefits of farm digitalisation in Europe” (Iliopoulos et al., 2025). These outputs documented a rich variety of perspectives. Stakeholders emphasised both expected advantages, such as efficiency gains, better decision-making, environmental improvements, and opportunities for new business models, but also major concerns including trust deficits, costs of adoption and maintenance, dependency on providers, lack of adequate skills, and risks associated with data governance and cybersecurity.

This section of Deliverable 4.2 provides an extended abstract of those findings, emphasising the methodologies, activities, and main results, and explicitly linking them to the published scientific article. In addition, it reports on new activities undertaken between M24 and M36, including further integration with environmental and economic analyses, refinement of data collection protocols, and preparation of a second round of focus groups to be held in 2025.

2.2 Scope and Objectives

The work conducted under this Section has a scope to capture qualitative, actor-centred insights into digitalisation. More specifically, its scope extends across:

- Geographical diversity. Covering 18 Living Labs across Europe ensures that results reflect different agro-ecological zones, farm sizes, market conditions, and institutional contexts, thus capturing heterogeneity in both opportunities and constraints.
- Multi-actor engagement. Including farmers, advisors, policymakers, technology providers, and researchers ensures that perspectives are not limited to single groups but reflect the entire ecosystem of digitalisation.
- Temporal relevance. By organising data collection in two phases (M18–M24 and a follow-up in 2025), the task is designed to capture both initial expectations and evolving perceptions as technologies mature and are tested in practice.

The **objectives** of this work are therefore:

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- To identify and categorise stakeholder perceptions of the C&B of farm digitalisation across multiple contexts.
- To analyse commonalities and divergences in perceptions, highlighting how regional, sectoral, and actor-specific differences shape attitudes.
- To inform subsequent tasks with actor-driven evidence, ensuring that economic models, environmental assessments, and social analyses integrate real-world perceptions.
- To contribute to scholarly debates through peer-reviewed publication, thereby enhancing the visibility, credibility, and transferability of project results.
- To support policy and practice, particularly the Common Agricultural Policy (CAP), digitalisation strategies, and the broader goals of the European Green Deal, by identifying adoption barriers and enablers.

2.3 Theoretical Background

The analysis of stakeholder perceptions of the costs and benefits of farm digitalisation is embedded in a broad body of literature that conceptualises digital agriculture as a socio-technical transition (Carolan, 2017; Zscheischler et al., 2022) and as part of wider transformations in agri-food systems. Existing research stresses that digital technologies are not neutral, but generate a variety of outcomes across economic, environmental, and social dimensions (Hidalgo et al., 2023; Ajena et al., 2022; Hackfort, 2021). These outcomes are contingent on governance structures, infrastructure, and the socio-economic contexts in which technologies are deployed.

From an economic perspective, scholars have highlighted that digitalisation can reduce production costs through efficiency gains and better allocation of inputs such as fertilisers, pesticides, and water (Getahunet al., 2024; Barnes et al., 2019; Van Evert et al., 2017). Evidence from Brazil (Bolfe et al., 2020) and Canada (Abdulai et al., 2024) suggests that productivity increases and profitability improvements are commonly perceived benefits. At the same time, studies report substantial barriers, including high upfront costs, recurring subscription fees, and risks of technological obsolescence that weigh disproportionately on smaller farms (Shehrawatet al., 2024; Deichmann et al., 2016).

The environmental dimension is also strongly emphasised in the literature. Digitalisation is often associated with potential sustainability gains, such as reduced input use and lower greenhouse gas emissions (Garske et al., 2021; Javaid et al., 2022; Finger, 2023). However, concerns are raised regarding increased energy demand, resource requirements for equipment, and rebound effects, whereby efficiency gains may drive production intensification (Ajenaet al., 2022; Hidalgo et al., 2023).

On the social side, research suggests that digitalisation may improve working conditions, free up time, and make agriculture more attractive to younger generations (Regan, 2019; Shehrawatet al., 2024). It can also support inclusivity by reducing physical labour demands and improving opportunities for women and youth (Regan, 2019). Yet, critical voices emphasise risks of deskilling, changes in farmers' autonomy, and widening digital divides between large and small farms (Rotz et al., 2019; Kernecker et al., 2020; Hackfort, 2021).

A recurring theme across the literature concerns trust, governance, and data rights. Farmers often express scepticism about who owns and controls agricultural data, how it is monetised, and whether advisory services or technology providers act in their best interests (Carolan, 2017; Klerkx et al., 2019; Arcuri et al., 2023). Perceptions of fairness and accountability are therefore central in shaping whether digitalisation is seen as an opportunity or a threat.

Finally, several authors stress that the adoption and diffusion of digital technologies are path dependent and context specific, influenced by infrastructure, policy incentives, and socio-cultural conditions (Ammann et al., 2022; Deichmannet al., 2016). For example, stakeholders in Northern and Central Europe tend to prioritise efficiency and precision gains, whereas those in Southern Europe emphasise inclusivity, social attractiveness, and modernisation effects (Iliopoulos et al., 2025). This aligns with socio-technical transition theory, which underlines that digitalisation functions as a niche innovation requiring enabling ecosystems, policies, advisory systems, and networks of trust to scale up and deliver on its promise of more sustainable agri-food systems (Geels, 2002; Shepherd et al., 2018).

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2.4 Methodology

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 AGRERI 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 categorized 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 Categorization: Themes developed inductively from data, aligned with focus group questions.
- Review & Synthesis: Researchers compared findings and agreed on final thematic categories.

Preliminary results were presented in DEL4.1 and are now peer-reviewed and published, ensuring methodological transparency and wider dissemination.

2.5 Main Results

A total of 148 Individuals with many different professions (farmers, advisors, policymakers, technology providers) participated in the focus group discussions. The median age was 48 years (range 22 to 57 years). Seventy participants (47.30%) identified themselves as female, and 48 (20.27%) as male, while the remaining 30 participants (20.28%) chose not to disclose their gender. In the discussion on the benefits of farm digitalization, three key themes emerged, whereas the subsequent discussion on its costs revealed nine distinct themes.

2.5.1 Perceptions of the benefits of farm digitalization

The benefits of digitalization are clustered around improving operations, opening up new business opportunities, and redefining the social and professional image of farming.

- **Time, decision making and planning**: Participants across different countries consistently emphasized the ability of real-time data and automation to cut down manual effort, enhance planning, and support quicker decisions
- **New business models in agriculture**: Precision technologies like sensors and data analytics improve productivity (e.g., optimized feed systems in France, soil scanners in Hungary) while modernizing agriculture's image to attract diverse talent and markets. Beyond operational gains, digital tools foster direct consumer engagement and circular practices, signaling a shift from pure production to value-driven, resilient farm enterprises.
- Social Benefits - Good to be a digital farmer: Digital tools are making farming a more attractive, efficient, and sustainable profession. Key benefits include enhanced job satisfaction, streamlined operations, and greater inclusivity, helping modernize agriculture's image and engage younger generations.

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2.5.2 Perceptions of the costs of farm digitalization

- Trust issues: Trust barriers significantly hinder agricultural digitalization, with farmers often viewing governments, tech providers, and consultants with scepticism. Concerns range from inadequate infrastructure and hidden costs to unreliable post-sale support, creating an “us vs. them” dynamic.
- Time and resources: Small farms face disproportionate challenges in adopting digital agriculture, including limited staffing, steep learning curves, and inadequate infrastructure. While larger operations can absorb these demands by hiring specialists, smaller producers often find digital tools create more complications than benefits due to interoperability issues, rapid obsolescence, and poor connectivity. Targeted support programs, simplified technologies, and improved rural infrastructure are essential to make digitalization viable for farms of all scales.
- Risks and uncertainties: The adoption of digital technologies in agriculture faces significant barriers, including economic burdens, technological obsolescence, data security risks, and operational complexity. Smaller farms are particularly vulnerable, struggling with high upfront costs, maintenance demands, and integration challenges. Additionally, regulatory compliance and resistance to changing practices further hinder adoption.
- Changing roles and skills: Digitalization is transforming farmers’ roles, shifting focus from hands-on labour to hybrid skills in technology management and data-driven collaboration. While this transition enhances efficiency, it risks detaching farmers from traditional fieldwork and requires continuous upskilling to keep pace with evolving tools.
- Governance issues: Farm digitalization raises critical governance questions regarding cost distribution, control, and benefit sharing among stakeholders. Farmers face financial burdens and uncertainty over technology ownership, data rights, and risk liability, with concerns that agribusinesses may disproportionately benefit.

The focus group discussions on the costs of farm digitalization uncovered a multifaceted landscape of challenges, ranging from trust and governance issues to resource limitations and access barriers. These themes underscore the complex interplay between technological advancements and the structural, social, and economic contexts in which they are implemented.

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).

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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.

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 Recommendations

Drawing on the stakeholder perceptions, several recommendations can be made to support a more equitable and sustainable digitalisation of European agriculture:

1) Improve trust and governance of digitalisation
- Establish clear, transparent frameworks for data ownership and use, including contracts that protect farmers' rights.
- Promote accountability and reliability among technology providers, ensuring long-term service and fair cost structures.

2) Enhance capacity building and advisory support

- Strengthen **advisory services** and create peer-to-peer learning networks to support farmers in adopting and using digital tools.
- Provide **targeted training opportunities** to reduce the skills gap and respond to generational differences in digital literacy.

3) Address cost and infrastructure barriers

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- Facilitate access to **affordable financing models** (subsidies, credit schemes, cooperative solutions) to reduce entry barriers for small and medium farms.
- Invest in **connectivity and interoperability** infrastructure, especially in rural and remote areas, to ensure equal opportunities for adoption.

4) Align digitalisation with sustainability goals

- Encourage digital tools that deliver measurable **environmental benefits** (e.g. reduced inputs, lower emissions) while monitoring unintended effects such as higher energy demand.
- Integrate digitalisation policies with the **European Green Deal** and **CAP objectives**, ensuring coherence between innovation and sustainability strategies.

5) Foster inclusivity and equity in adoption

- Tailor policies to **different farm sizes, sectors, and regions**, recognizing that digitalisation will not progress uniformly.
- Support models that empower **women, youth, and smallholders**, reducing risks of exclusion and dependency.

2.9 New activities between M24 & M36

During the period between M24 and M36, Task 4.2 moved beyond data collection and preliminary reporting to dissemination and consolidation of findings through several scientific outputs and conference presentations. These activities significantly increased the visibility and impact of CODECS results:

1) Peer-reviewed publications

- Iliopoulos, C., Theodorakopoulou, I., Giotis, T., & Brunori, G. (2025). Perceptions of costs and benefits of farm digitalization 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

These two publications complement Deliverable 4.1 by presenting the empirical findings and methodological contributions to both scholarly and practitioner audiences. The IFAMR article emphasises methodological transparency and cross-country analysis, while the EuroChoices article targets European stakeholders and policymakers with accessible insights into adoption barriers and enabling conditions.

2) Conference dissemination

- Findings were presented at the *Regional Studies Association's Annual Conference 2025* under the title *"The Perception of Costs and Benefits of Farm Digitalisation in Europe"*. This provided an opportunity to share results with an interdisciplinary audience of regional scientists, policymakers, and practitioners, stimulating discussion on the territorial dimensions of agricultural digitalisation.

3) Contributions to the CODECS Newsletter

- Two blog posts were published in the CODECS Newsletter to further disseminate findings: one summarising the IFAMR publication and one reporting on the RSA Conference presentation. These contributions targeted the wider CODECS community and external stakeholders, reinforcing project visibility and impact.

2.10 Upcoming activities

- 2nd Focus Group : The next step for task T4.2 is to prepare with the Living Lab Coordinator the second Focus Group on Perceptions of Costs and Benefits of digitalisation in agriculture. This FG should take place during the third and last LL Workshop in January/Feburary 2026.

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A new set of questions will be prepared and the Living Labs will be trained. In addition, new guidelines for reporting the outputs of the Focus Groups will be provided.

- Further data analysis with inputs from other tasks (T4.5)
- Reporting activities

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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 Montpellier)

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 categorize 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 standardized, 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 analyzed 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 digitalization. They also help identify hotspots—steps in the process with particularly high environmental impacts. The environmental assessment in CODECS utilizes 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 digitalization 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 standardized, 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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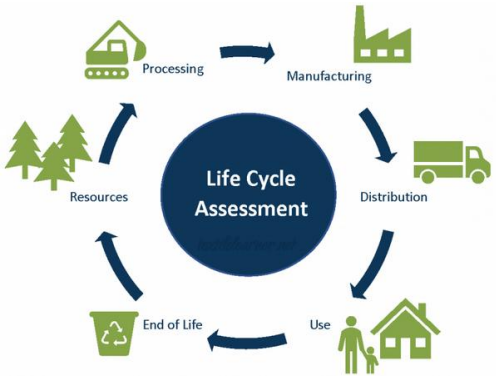

Figure 3: Scope of the LCA

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 characterizes 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.

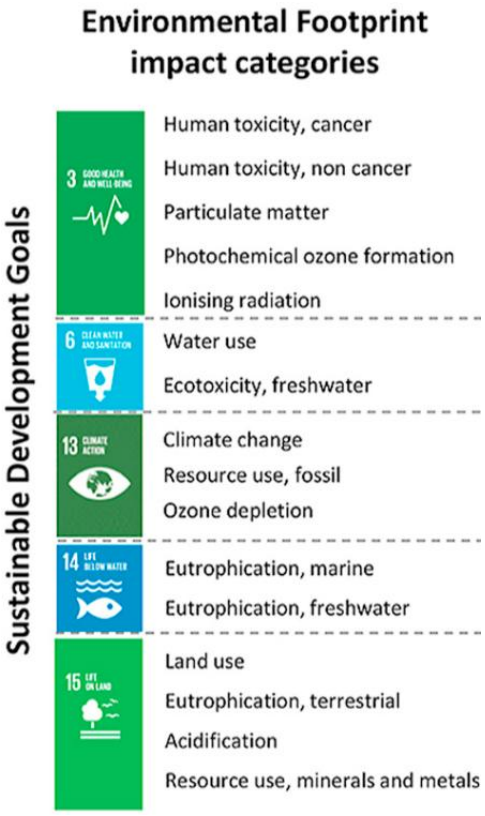

Figure 4: Environmental impact categories in LCA (and link to the SDG)

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:

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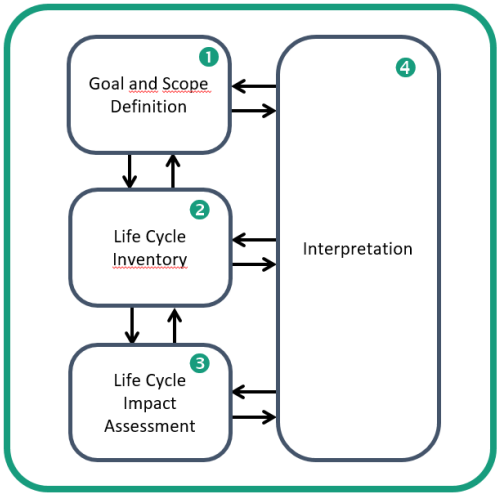

Figure 5: LCA steps

- 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

This section provides a short synthesis of the state of the art of Environmental assessment of digitalisation in agriculture based on the following review paper: ***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***, which systematically reviews the environmental impacts of digital agriculture technologies (DATs) and examines these impacts using the Life Cycle Analysis (LCA) framework.

3.3.1 Scope and Methodology

The review systematically analyzed 69 studies published between 2008 and 2024 that assessed the environmental impacts of DATs in agriculture. The majority of these studies focused on crop production, with a smaller number addressing livestock production and supply chains. The DATs reviewed were categorized into four main groups: technical production management (TPM), robotics and automation, strategic decision support, and traceability. The analysis was conducted using the PRISMA method and focused particularly on studies employing the LCA framework.

3.3.2 Key Findings

Digital Agriculture Technologies (Figure 6**) :**

- Technical Production Management (TPM): The majority of DATs reviewed fell under TPM, which includes technologies such as variable rate prescription maps, optical sensors, and satellite imagery. These technologies primarily aim to optimize input use, such as fertilizers and irrigation, thereby potentially reducing environmental impacts.
- Robotics and Automation: This category, representing nearly a third of the studies, includes robots and automated systems designed to reduce human labour and improve precision in agricultural operations. However, these high-tech solutions often come with significant environmental costs due to their energy use and the materials required for their production.
- Strategic Decision Support and Traceability: These categories were less represented in the literature but are crucial for improving logistics and reducing food wastage across the supply chain.

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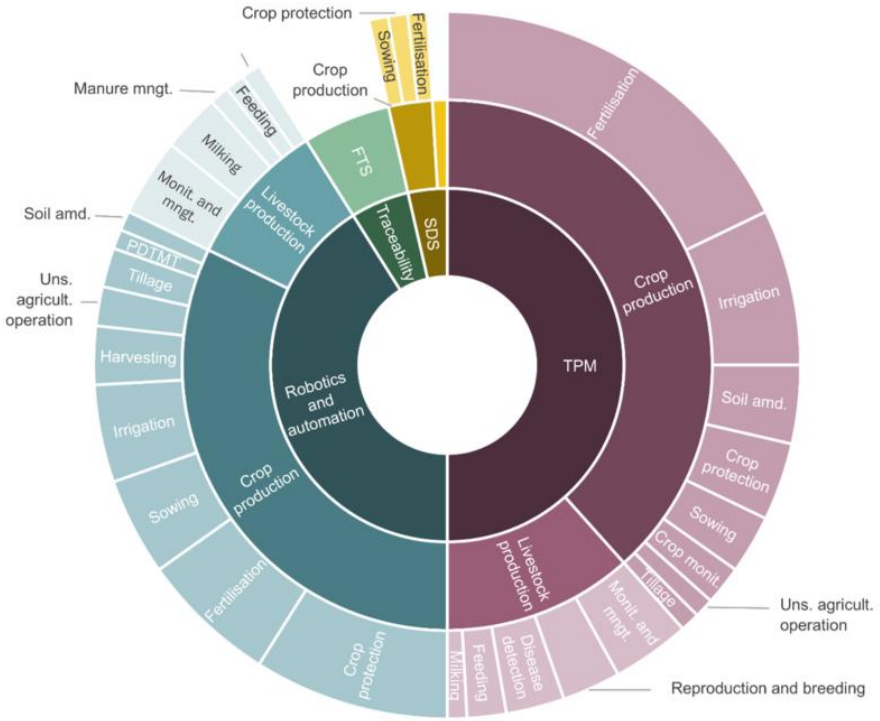

Figure 6: Service provided by type of digital technologies: TPM (technical production management), robotics and automation, traceability, and strategic decision support (SDS) in relation to the agricultural sector (crop and livestock) and agricultural operation (adapted from Huck et al. 2024).

Environmental Impacts

- The review highlighted that most studies concluded DATs reduce environmental impacts, mainly through efficiency gains and the substitution of electricity for fossil fuels. However, the extent of these benefits varies widely depending on the specific technology and its application.
- Some studies reported increased environmental impacts, particularly when high-tech DATs such as robots and UAVs were considered. These impacts were primarily associated with toxicity, resource use, and the environmental burdens of the technology's life cycle (production, use, and disposal).

Methodological Challenges

- Functional Unit and System Boundaries: The choice of the functional unit (e.g., mass of product or cultivated area) and the system boundaries (what is included in the assessment) significantly influence the outcomes of the LCA. The review found that many studies did not fully include the DAT life cycle in their assessments, potentially underestimating their environmental impacts.
- Data Availability: There is a lack of comprehensive data on the environmental effects of DATs, particularly regarding their production and end-of-life phases. This has led to the use of proxies and assumptions, which can introduce uncertainty into the results.
- Impact Assessment: The choice of impact indicators, such as global warming potential or eutrophication, also varied across studies, influencing the interpretation of results. Most studies focused on midpoint indicators, but there is a growing interest in endpoint indicators that could provide a more holistic view of environmental impacts.

3.3.3 Recommendations

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The review article provides several recommendations for improving the environmental assessment of DATs:

- Comprehensive System Boundaries: Future LCA studies should include the entire life cycle of DATs, especially for hardware-intensive technologies. This includes production, use, and disposal stages, as these often contribute significantly to environmental impacts.
- Use of Multiple Functional Units: Employing both mass-based and surface-based functional units can provide a more comprehensive assessment of the environmental performance of DATs, capturing both production efficiency and land-use efficiency.
- Enhanced Data Collection: Collaboration with DAT manufacturers and the use of up-to-date databases are crucial for improving the accuracy of LCA studies. Proxies should be used judiciously, and assumptions should be clearly stated and tested through sensitivity analyses.
- Broader Impact Indicators: Selecting a broad range of impact indicators and justifying their choice can help capture the full spectrum of environmental impacts associated with DATs.

3.3.4 Conclusion

This systematic review underscores the potential of DATs to reduce the environmental impacts of agriculture but also highlights significant challenges and uncertainties in their assessment. As digital agriculture continues to evolve, it is essential to refine LCA methodologies and expand data collection efforts to ensure that the environmental benefits of these technologies are accurately quantified. However, this review lays the foundations for the methodology to be applied to the CODECS Living Labs use cases.

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 digitalized process) (Figure 7).

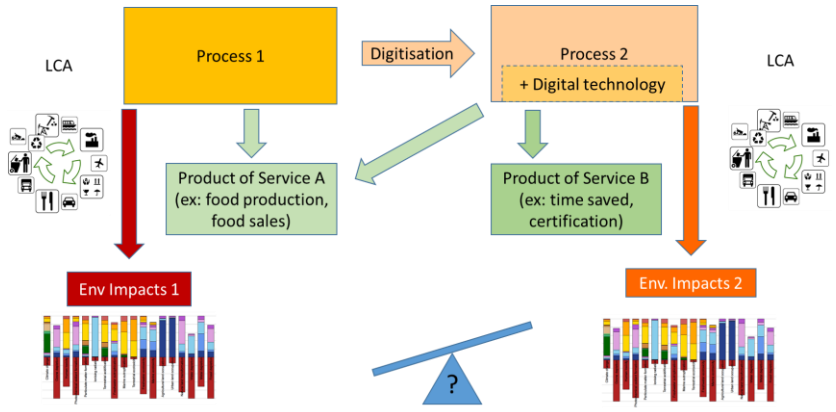

Figure 7: Principles of comparative LCA in the context of farm digitalisation in CODECS

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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 analyzed 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).

The following criteria are:

(i) **State of digitalization**:

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

Based on these criteria, the Living Labs were classified according to the feasibility of conducting LCAs on their use cases (Table 1):

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Table 1 : LL Classification and Type of environmental analysis

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

In order to fulfill the Life Cycle Inventory, which comprises both the data about the agricultural production system and the digital technology, it is important to identify which data are mandatory for the analysis to be performed and which data are facultative. Our objective being also to limit the workload of the Living Lab coordinators and the interviewed farmers.

Therefore, we suggested to tailor the data collection file to each specific use-case and to do so, we based the definition of the Goal and Scope step on the information provided by the Living Lab Coordinators in the T3.3 Report, where the different processes (before and after digitalisation are described).

We validated this stage with the Living Labs coordinators during a one-to-one discussion, which enabled us to clearly define the different scenarios, the level of transformation brought about by the use of technology and, finally, to assess the LL's ability to provide the data needed to carry out the LCAs.

It should be added here that these interviews enabled us to validate the goal and scope (scenario) + availability of data.

After this step is fulfilled, the data collection files have been adapted for each selected the Living Lab. See the Supplementary material section which presents an example of Data Collection File.

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3.5 Forthcoming steps

The main activities will be dedicated in finalising the LCA analysis for the 12 LL that have provided quantitative data. For the other ones, we will compute the existing qualitative data from other sources to be able to provide to each LL an Environmental Analysis Report (Practice Abstract).

- M36 – M42: LCA of 12 use-cases in CODECS LL: individual report + Practice Abstract + Data for EFC (Scenario building)
- M36 – M42: 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 (8LL)
- M 42: synthesis report of the environmental impacts of farm digitalisation part 3 (in D43)

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

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4.1 Introduction

The current section 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 economic costs and benefits that derive from the adoption of digital technologies and their application in farming. The chapter describes the objectives of CODECS and of Task 4.4 followed by the proposed methodological framework for the identification and estimation of economic costs and benefits as well as the data collection process that is underway to accommodate the economic analysis.

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 digitization and consequently from the digitalisation of farming. Digitalisation offers farms significant potential to enhance efficiency, profitability, sustainability and decision-making. However, these benefits must be weighed against the costs of acquisition, installation, integration and operation of the digital technologies. Conducting an economic costs and benefits analysis enables farmers, investors, advisors and policymakers to assess the financial viability of such technologies by comparing expected cost savings, productivity gains, and potential revenue increases with the associated capital and operating expenditures. The results of the analysis will assist them in understanding and predicting the benefits and costs of adopting digital technologies and explore optimal solutions and alternative options for their farms. Task 4.4 is dedicated to caring out this structured evaluation that will support informed decision-making, helping stakeholders determine whether the investment they are considering will generate a positive return over its useful life The results of Task 4.4 will also be useful to the CODECS consortium.

Specifically:

- The economic costs and benefits will be integrated in the multicriteria assessment of Task 4.6 and trade-offs will be estimated.
- The methodological framework, the data collection materials and questionnaires, the case studies and the results of the economic analysis will also facilitate the development of the economic cost and benefits calculator of WP7.
- Results will be used in dissemination actions of WP1 and in the LL Workshops.
- The results of the task will also be available to policy makers that design and implement measures for farming digitalisation (Contribution to Policy Brief 9: Economic co-benefits and costs of digitalisation).

Finally, through the estimation of economic costs and benefits, the identification of main elements, barriers and bottlenecks of the digitalisation process will be revealed and ways to tackle them will be suggested.

In order to achieve its objective, the economic analysis of Task 4.4 will utilize a mixed methods approach based on qualitative and quantitative data gathered from LLs and demonstration farms, available literature, accountancy records, log books and other available data bases.

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4.3 Theoretical Background

Digitalisation is perceived by farmers and agri-food stakeholders to hold many economic benefits such as enhanced productivity and profitability of farms and reasonable return on investment (Abdulai et al, 2024). The economic benefits of digitalisation may arise from decreased costs due to decreased input use, such as fertilizers, agrochemicals and fuel, but also from an increase in crop yield (Bucci et al., 2020). According to Kolmykova et al. (2021), digital technologies in agricultural enterprises reduce labour intensity, enhance labour productivity, and increase both resource efficiency and the quantity and quality of crops. Though a large body of literature argues the benefits of digitalisation, still there is a gap on empirical studies that support this argument (Šermukšnytė-Alešiūnienė and Melnikienė, 2024), while others even contradict it and emphasize the risks of digitalisation (Visser et al., 2021). That said, it is clear that further research is required to identify not only the costs and benefits of digitalisation but also explore factors that affect these costs, like farm-size, government support, compatibility of the technology (Ferrari et al., 2022).

Within CODECS, the economic analysis will focus primarily at the farm level, as this is where decisions about adopting digital technologies are made (Munz, 2024). Farms are also the physical place where resources are combined to produce outcomes, while farmers' expectations regarding costs and benefits constitute the primary driver of agricultural digitalisation, making them the key actors in this process. However, depending on the case study, the type of digital technology applied, the digitalisation level and the data availability, the analysis may only focus on specific processes within the farm.

The economic analysis will consider both transition costs, i.e., the initial investment required to adopt, install and integrate digital technologies, and operational costs, i.e., the annual production costs associated with maintaining these technologies. Transaction costs i.e., costs linked to legal, regulatory, or administrative processes around adoption, were also considered in the economic analysis.

It is also important to highlight that the adopted methodological framework for economic analysis follows a cost-benefit approach and relies on ex-post evaluations (Barrientos-Fuentes & Berg, 2013; Maredia et al., 2014). The analysis will compare pre-adoption and post-adoption periods to assess the associated costs and benefits (Bucci et al., 2020).

4.4 Methodology in CODECS

4.4.1 General methodological framework in CODECS

This section of the deliverable contains the general methodological framework for the estimation of the economic costs and benefits that derive from the digitalisation of farming. 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 is also designed to be compatible with the economic costs and benefits calculator of WP7, and therefore will facilitate its development.

The economic analysis methodological framework, involves a mixed-methods approach, based on both quantitative and qualitative data collected from the farms in the Living Labs, and utilizes methodologies commonly used in agricultural economics. Figure 8 represents this proposed multi-step and data driven methodology for the economic analysis.

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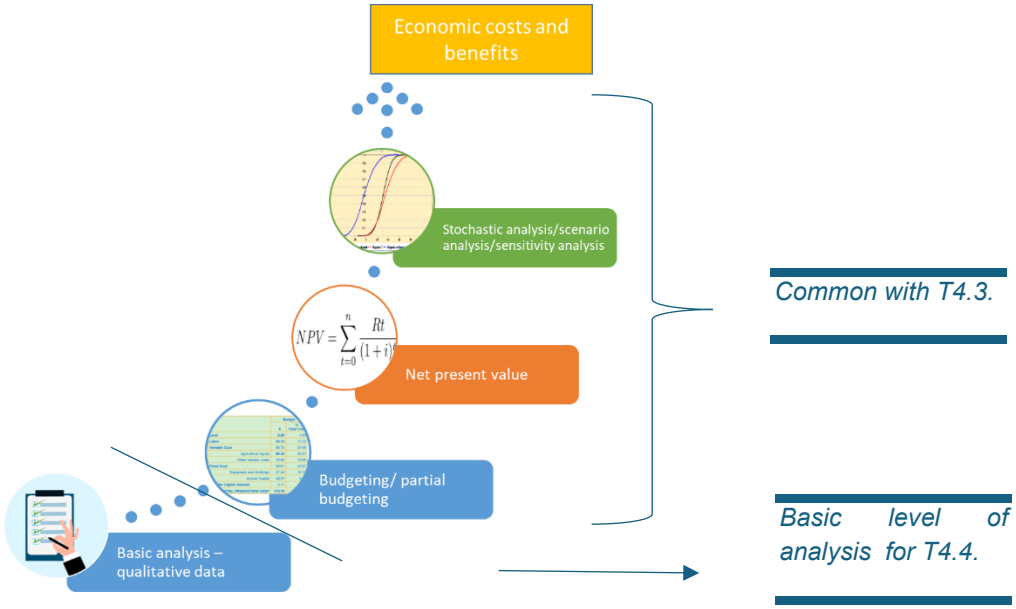

Figure 8 Mutli-step methodology for economic analysis, tailored for each LL

4.4.2 Basic economic analysis

The first level of the methodological framework, as shown in Figure 8, involves mainly a qualitative analysis, particularly in cases where farm data are limited. This step can be applied to all Living Labs (LLs), including those that have not yet begun digitalizing, as it requires minimum quantitative information. The goal of this phase is to identify potential economic costs and benefits, even when quantitative farm data are unavailable or difficult to estimate.

To this end, 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 even if the LLs cannot provide quantitative data. For this reason, only the questions that refer to qualitative data are mandatory. In the cases of LLs, that only qualitative data on economic costs and benefits can be provided, the basic analysis will be limited to a representation of the relevant costs and benefits. As a result, this basic economic analysis will complement the more detailed findings gathered from in-depth interviews.

4.4.3 Budget analysis

The main step of the economic analysis involves the construction of a whole-farm budget table or partial budget table depending on the use-case in the Living Lab. Budgeting and partial 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 change. It is a very useful and easy to apply management tool that summarizes input requirements and additional benefits, expressed in monetary terms either for the whole farm, a single enterprise or process within the farm. The construction of farm

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budget or partial budget will also allow for the estimation of productivity indicators for main resource units (e.g., labour or land productivity) and economic outcome indicators like net profit and income (Ahmed et al., 2021).

4.4.4 Net present value

Net Present Value (NPV) analysis will also be performed in the cases that quantitative data is 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 us 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 will be available from the Budget Table, described in the previous paragraph.

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

To account for economic risk, sensitivity analysis can be contacted, 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 us 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.

4.4.5 Stochastic budgeting/NPV analysis

A more advanced methodology that can be used within the cost-benefit methodological framework to account for the economic risk is the Stochastic Budgeting Analysis or Stochastic NPV analysis (Bewley et al., 2009; Tzouramani et al., 2011; Liontakis et al., 2021). Most of the methods used in cost-benefit analysis assume deterministic values for cost and income elements (e.g., prices of inputs and products and yields). But deterministic economic models do not take into account possible differences in the riskiness of net income between alternative technologies or practices. In stochastic models, deterministic values of key cost and income elements are replaced with distributions of values and the stochastic model estimates the probability of an economic outcome (e.g., profit) to occur providing the farmer with a range of values (minimum, maximum and mean economic outcome). In the case of the NPV for example, the desirability of the investment is estimated not by producing a deterministic NPV but a whole distribution that links all feasible NPVs with specific probabilities (Liontakis et al., 2021).

In order to rank alternative technologies or practices first and second-degree Stochastic Dominance analysis can also be implemented (see also Mutenje et al., 2019).

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This step of the methodological framework will be performed only if data is available, since it requires the construction of distributions of main variables like prices or yields.

4.5 Data collection framework

For the economic analysis two complementary data collection surveys are currently taking place:

4.5.1 Online data collection survey for economic costs and benefits.

As already mentioned in the methodological framework, in order to run the basic economic analysis, identify and present the main costs and benefits stemming from the adoption of digital technologies, an online questionnaire was developed. The questionnaire is built to accommodate data collection from farms with various degrees of digitalisation, since it incorporates qualitative and quantitative data, only the qualitative questions are mandatory, while providing quantitative information is optional and can be filled out only it the data is available. The structure of the questionnaire, together with the consent form, the information sheet and the main instructions to the users can be found in the Supplementary material section.

A hard copy of the questionnaire was originally presented to the LL coordinators during the online training course that took place in February 2025. After feedback received from inside the CODECS consortium the online version of the questionnaire was developed and tested. The final version of the questionnaire was distributed to the LL coordinators at the end of June 2025. The LL coordinators were given the option to either provide the link to farmers so that they can directly complete the online questionnaire or interview the farmers using a hard copy of the questionnaire and then fill out the online questionnaire with the farmer's answers.

Access to on-line questionnaire here.

4.5.2 Face-to-Face in depth interviews for technical and economic data

Within the in-depth data collection survey, data is collected at the farm level through farmer interviews organized by the Living Lab Coordinators. This approach provides access to accountancy records, logbooks, and specific quantitative information. Common data collection materials are developed in collaboration with Task 4.3 (Environmental Analysis), as the same type of quantitative data is required for Life Cycle Analysis (LCA).

In order to tailor the data collection materials for each case study, one-on-one online meetings with LL coordinators and the research teams of T4.3 and T4.4 took place in March 2025 and April 2025. The meetings aimed to help the research teams understand the digitalisation procedure of each case study, so that they can prepare the questionnaire for the interviews as well as train the LL coordinators on the basic principles and the recommended process of the data collection. During these meetings, it was explained to the LL coordinators that they are responsible for the following tasks:

- **Identify the farm(s) to be assessed**: Check if the farm will be able to provide quantitative data about the production system, before and after the digitalisation process
- **Organise the in-depth interview**: set the date for a 1 – 2 h slot, if possible in presential. This meeting can also be articulated with other activities in the LL: in-depths interview for Social C&B for example, or for completing data collection for WP3.
- **Send the questions in advance**: this will help the farmer identify the sources of data (log books for example)
- **Conduct the interview**: With the help of the specific questionnaire prepared by task leaders.
- **Prepare the reporting**: Complete the data collection file

During the weeks after the meetings, the data collection materials and files for each case study was prepared and shared with the LL coordinators who were also provided with instructions for the data collection process and reporting procedures. Supplementary material section which presents an example of Data Collection File.

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This in-depth data collection process is currently underway. For each LL, the data collected will be reviewed for inconsistencies, and will be coupled and analysed together with the data from the online survey. The research team will also conduct the LL coordinators if additional information or clarifications are required. Feedback from the living labs will be used to validate the analysis and the findings, and the final results will contribute to the production of reports, briefs, and other deliverables.

Outputs

The data requirements for the economic analysis that will be met by the in-depth survey, are presented in the Supplementary material section and include estimates of annual land costs, agricultural input costs, labour costs, and fixed capital costs e.g. depreciation, interests (Gangwar et al., 2022). Annual costs specific to digital technologies, such as additional inputs, are also considered (Wassman & Pathak, 2007). Transition costs may include acquisition, installation, maintenance, software updates, hiring specialists, and staff training (Ivanov & Webster, 2017). Some of these costs are required also in the online survey, but in the in-depth interview they are required in more detail, which will be useful for any additional estimation. For example, if an alternative to the used digital solution is available, there can be a comparative economic analysis between the two solutions.

It is important to emphasize that only a small number of cases/farms within the CODECS LLs have already adopted and used the digital technologies. Therefore, the in-depth questionnaire for the economic and environmental evaluation will be used in a limited number of farms. Though this will not lead to statistical representation of European farms, the single-case design has been adopted in many studies and has scientific value since it may lead to a better in-depth understanding of the processes (Bucci et al., 2020).

4.6 Forthcoming steps

- M36 – M42: Finalise the use cases Economic analysis, both for in-depth analysis and Investment costs analysis
- M36– M42: Communication set for each LL to present results in demo (complete the Practice abstract)
- M 42: synthesis report of the environmental impacts of farm digitalisation part 3 (in D43)

4.7 Conclusions

The previous paragraphs outline the methodology used, along with the data collection surveys currently under way, for identifying and estimating the economic costs and benefits of digitalisation. This task presents several challenges, as many of the CODECS Living Labs (LLs) have not yet fully digitalised, making it difficult to provide sufficient data for a comparison of “with” and “without” the digital technologies’ scenarios. As a result, the economic analysis methodology and data collection process is adapted for each LL according to their level of digitalisation. Also, complementary to the in-depth data collection survey, an online survey for the collection of qualitative and quantitative data is implemented. For LLs currently in the process of digitalising, only qualitative data and/or quantitative data on transition costs will be collected and presented, through the on-line survey.

For LLs that are already using digital technologies, both the in-depth questionnaire and the online questionnaire will be used to estimate economic costs and benefits, as well as the Net Present Value (NPV) of the digital technology investment. Risk analysis will be conducted based on data availability, using either stochastic analysis or sensitivity analysis. Alternative scenarios may also be explored, such as comparing the NPV with or without subsidies, depending on the specific case study.

The methodological framework outlined in this document was implemented in the Slovenian Case study on the Doppler Winery. The results of the case study were also presented in this document to demonstrate the benefits of digitalisation as well as the usefulness of the economic analysis to stakeholders.

The economic analysis will provide valuable information for farmers considering the adoption of digital technologies, as well as for their advisors. It will offer a range of costs and benefits associated with these investments, whether qualitative or quantitative, and suggest options to maximise benefits and minimise risks. The results will also be

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useful for policymakers, giving them a clear understanding of the economic impact digital technologies can have on farms, and enabling them to design effective measures to promote the uptake of viable digital solutions.

It is important to note that this deliverable will be updated, as the data collection surveys evolve and more LLs will participate in the surveys. Therefore, this document represents ongoing work by the partners involved in WP4.

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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 are being 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–M30) 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 aforementioned 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 are conducting a qualitative study among farmers identified in the CODECS Living Labs. This encompasses both positive and negative human changes affecting farmers and their agricultural practices. Social-human aspects include exploring the changes 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 aim 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 organized 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 9 shows some examples found in France of human-centred costs and benefits of digitalisation for five groups, organized into three main human components.

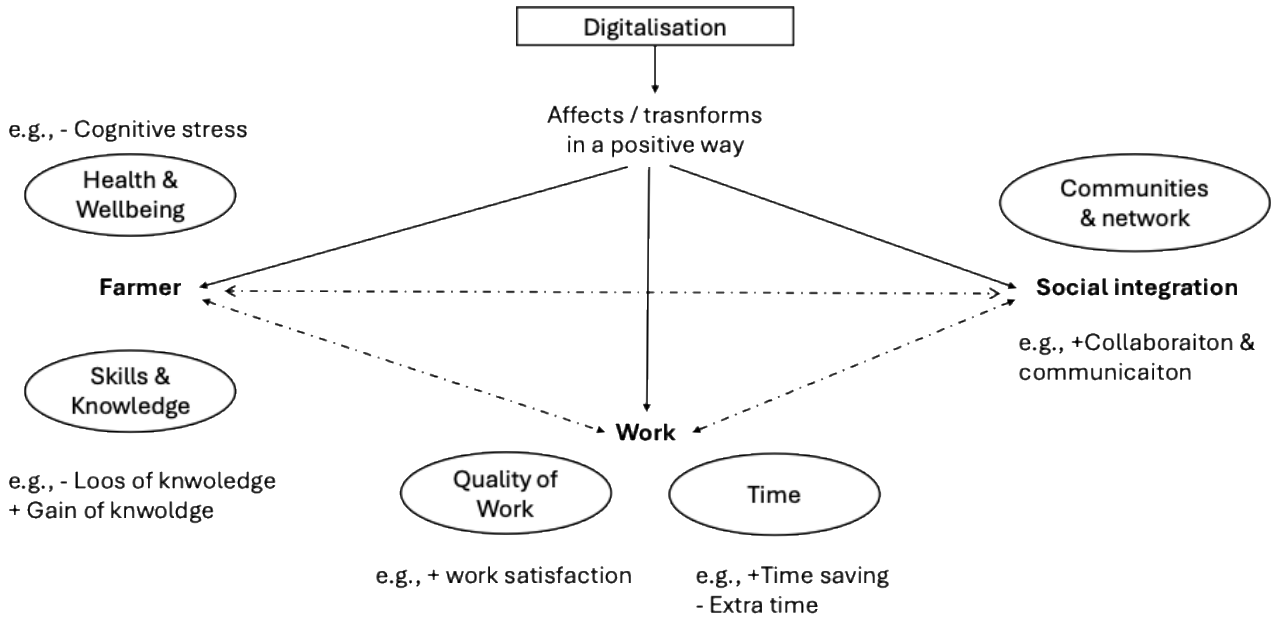

Figure 9: Human-centred Cost and Benefits digitalisation at the farm level

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.

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.

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Data for this stage of research is 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 us 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 2: Description of the collected data in T4.5 (M18 – M36) 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 2: 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

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independently coded their assigned interviews; (iii) team members compared outputs and resolved discrepancies; 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

5.4.1 General overview

The interviews confirmed the workshop themes and added finer-grained human costs and benefits of digitalisation related to mental wellbeing, identity and everyday work. Figure 10 shows the human centred costs and benefits of farm digitalisation. The results are structured around three themes: human wellbeing, work organisation and social integration. Each theme is divided into two categories, costs and benefits, which capture both positive and negative experiences of digitalisation. Within each category, subcategories further specify the findings.

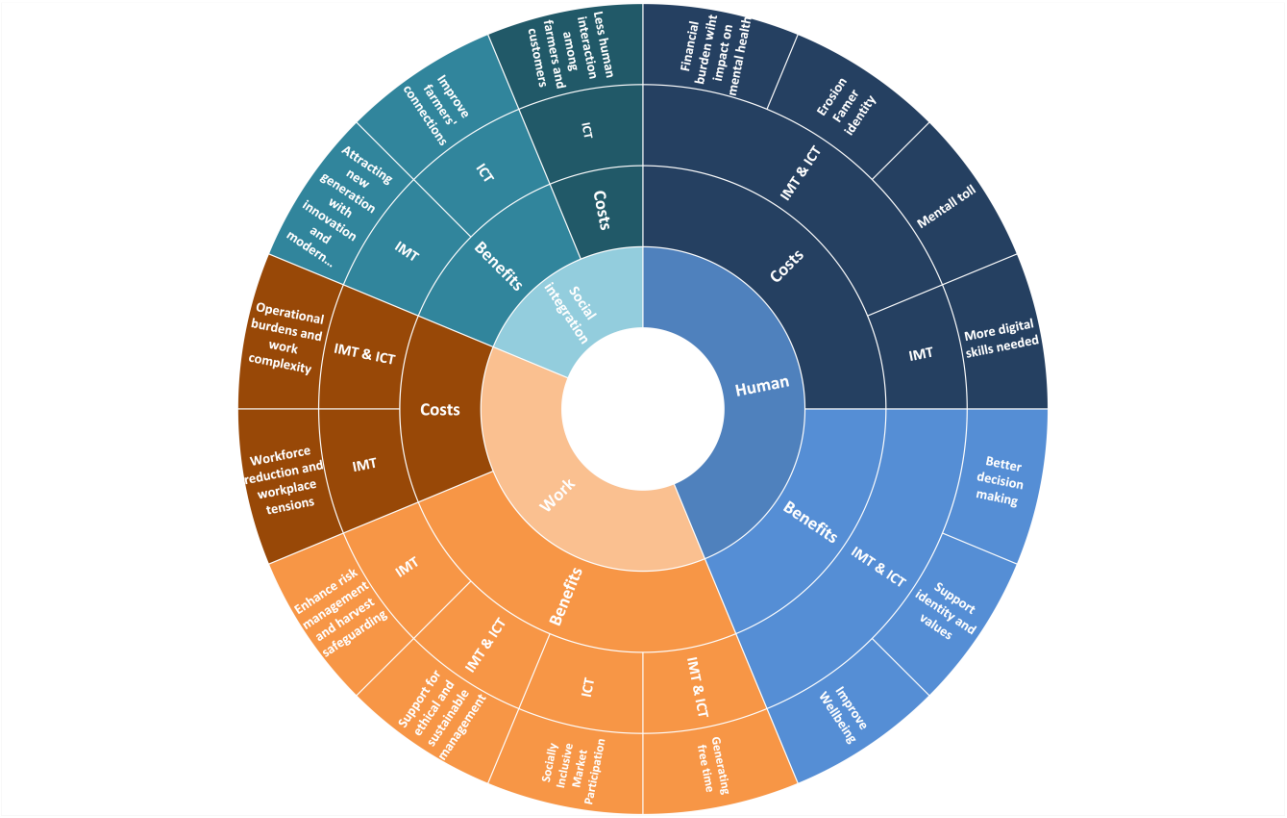

Figure 10 Human centred cost and benefits of farm digitalisation

Note: The sunburst diagram illustrates categories, subcategories and themes from the results but does not indicate their relative weight or frequency

Digital tools, Input Mangement Technologies (IMT) and Information Communicationn 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

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and at home. These findings highlight how efficiency and modernisation are closely tied to emotional strain and shifting social dynamics in agricultural work.

5.4.2 Human-centred Costs of Farm digitalisation

Digitalisation in farming entails notable costs that extend beyond financial investment. Farmers report cognitive overload, reduced autonomy, and continuous demands for new skills, with these pressures closely associated with stress. At the operational and social levels, issues of complexity, labour tensions, and diminished human interaction further highlight the risk of added burdens when technologies are poorly aligned with farm realities

Costs Affecting Individuals

Mental strain: cognitive overload from abundant, hard-to-use data and constant connectivity that encroaches on family time.
"It [data]… a full screen of numbers, and it's unusable…" (F6) • "I've got my phone in my hand constantly… trying to restrict screen time." (F10)

Identity and autonomy erosion: a shift from sensory, outdoor craftwork to desk-based oversight; diminished self-repair capacity.
"The job becomes an office job… you distribute tasks to robots and drones…" (F2) • "Digitalisation stops the farmer from being able to fix their own machinery." (F17)

Financial pressure (felt via well-being): high entry costs and recurring fees amplify uncertainty and stress, especially for smaller farms.
"…it's expensive and you might not recoup the cost." (F7) • "If anyone wanted a refund… you didn't get your fees back."(F8)

Continuous skills burden: steep learning curves for interconnected systems, thin vendor support, and age-related divides.
"…all these connections… were quite overwhelming…" (F6) • "If I don't take this step… I will be left behind by technology." (F2)

Costs Affecting Work Operations

Operational complexity: duplication, poor interoperability and tools misaligned with real farm routines increase administration and friction.
"The registration systems have to be duplicated…" (F16) • "Online shops… I saw it as a burden…" (F20) • "[Software]… problems in our operations." (F15)

Labour displacement and tensions: automation reduces certain roles; uneven digital readiness creates intra-team strains.
"…fewer job opportunities for people…" (F11) • "…only one… managing this [input-management technologies], it can create tensions." (F7)

Costs Affecting Social Integration

Thinner human contact: always-connected systems can displace face-to-face exchange and community routines.

"If you digitalised everything then just disconnect… human-to-human interaction." (F17)

Interim synthesis (costs): digitalisation often adds complexity, workload and stress when design and support do not match farm realities; large investments and perpetual upskilling are persistent pain points.

5.4.3 Human-centred Benefits of Farm digitalisation

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Despite the costs, farmers also reported clear human benefits: improved comfort and safety, stronger risk management and confidence, richer knowledge, better social coordination and environmental gains that feed back into well-being.

Individual Social Benefits

Better working conditions and safety: remote monitoring, automation and precision agriculture reduce travel, effort and exposure.
"…I do not have to go and check every day physically…" (F12) • "…more productive with less physical effort." (F19) • "…apply the pesticides with a drone… improve my father's health." (F19)

Flexibility and family life: ICT and e-commerce enable mobile management and continuity in changing places.
"Online sales… from my phone, basically." (F10) • "…keep us in agriculture… rapidly urbanising." (F20)

Identity and values, upgraded: data-informed, knowledge-driven farming; platforms to signal authenticity and origin.
"Being a farmer is no longer a dead-end profession…" (F7) • "…what matters… is authenticity… place of origin." (F20) • "These data sets will help us… economically and ecologically." (F2)

Benefits for Work

Risk management and planning: weather/IoT and end-to-end tracking support anticipatory, tailored decisions.
"…data from the weather station… easier to manage…" (F19) • "IoT… very important for… honey production." (F4) • "It tracks all our activities… helps us select…" (F3)

Ethical and sustainable practice: animal-welfare gains and resource efficiency with visible environmental co-benefits.
"…avoid unnecessary milking time." (F7) • "…more even spread… positive impact on the environment." (F6) • "…healthier animals, and a safer environment." (F11) • "…biodiversity mapping." (F1)

Market agency and time: direct sales increase control; digital planning frees time.
"Online sales… made it possible to run the business…" (F20) • "…digitalise some processes… create… free time." (F11)

Benefits for Social Interaction

Denser coordination and knowledge-sharing: always-on voice and peer data flows knit teams and neighbours.
"…voice messages… quick turnaround and efficiency…" (F17) • "Friends… call me to ask about the temperature…"(F12)

Appeal to new entrants: modern, well-equipped farms attract workers and younger generations.
"…makes the job more attractive…" (F6) • "…our hope to attract more younger generations." (F19)

Interim synthesis (Benefits): when tools fit context and support is adequate, digitalisation lifts working conditions, safety, planning and market power, while reinforcing community ties and environmental stewardship; policy and advisory efforts should amplify these gains and design out the known social costs—especially cognitive load, misfit tooling, financial barriers and uneven capabilities.

5.5 Discussion

This study examined the human centred costs and benefits of digitalisation at farm level, drawing on scientific workshop and interviews with 24 farmers across Europe. Findings show that digital tools shape personal wellbeing, work organisation, and social relations. While automation reduced physical strain and improved safety, financial burdens and limited support created frustration and stress. Constant connectivity and complex data management contributed to technostress and blurred work life boundaries. Farmers' professional identities were reshaped, with some positive feeling empowered by modern, knowledge-driven roles and others with the negative feeling of disconnected from hands-on practices. Digitalisation reorganised labour, privileging digital fluency, however sometimes reinforcing inequalities. Benefits included improved planning, sustainability practices, and expanded

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networks, yet human cost emerged from fragmented systems and skill gaps. ICTs strengthened communication and visibility but sometimes weakened local cohesion. Overall, digitalisation is not just technical change but a transformation of how farmers live, work, and relate to others. Future strategies must therefore address both operational needs and human realities.

5.6 Upcomming steps

- Provide tailored feedback to each Living Lab interviewed in terms of their human-centred cost and benefits
- Design quantitative tool to asses human-centred costs and benefits of farm digitalisation
- Knowledge diffusion was pursued through scholarly outputs, where data and interpretations developed during the project were consolidated into scientific article submitted on 21 June 2025
- Exploring knowledge diffusion between task 4.2 and 4.5 in terms of human-centred cost and benefits of farmers and stakeholders.

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6 Pilot USE CASE – Smart Villages Network LL – SLOVENIA

6.1 Objectives and general approach

Farm digitalisation, considered as the adoption and use of digital technologies in farming systems, transforms, in a positive or negative way; a large number of components of the system. The objective of the work carried out in WP4 of the CODECS project is to capture these changes to analyse the environmental, economic and social costs and benefits of the digitalisation of agriculture.

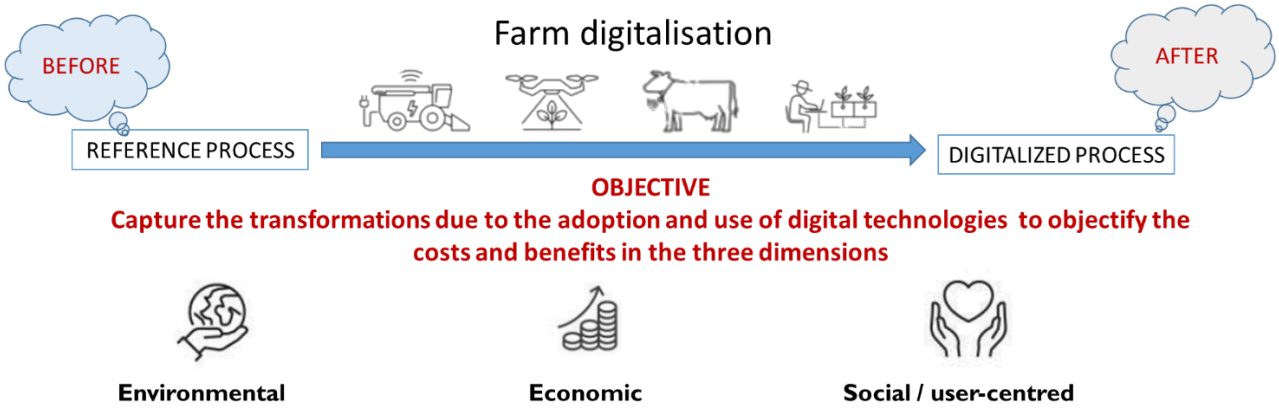

Figure 11 General approach of the C&B analysis of digitalisation at farm level

This section presents the Slovenia's Living Lab, *Smart Villages Network (SVN LL)*, one of the pilot cases assessed in WP4 of the CODECS project. It illustrates both the data collection process and the type of results obtained from the cost-benefit analyses of farm digitalisation.

These results have been summarised in a form of **Practice Abstract** document so that they can be presented to the LLs stakeholders and discussed during demonstrations activities (WP5) on the costs and benefits of using these IoT sensors. This Practice Abstract is presented in draft format in the Supplementary Material Section.

6.2 Use-case presentation

6.2.1 Focal Action Situation of SVN LL (based on T3.3 process report)

The Smart Villages Network Living Lab is located in three regions of Slovenia, bridging the east and west of the country. It brings together farmers, researchers, technology providers, and public authorities to test and develop digital innovations, with a particular focus on viticulture and beekeeping.

Over the years, the LL has experimented with IoT-based solutions. Persistent challenges have included rugged terrain, patchy network coverage, and the need for reliable, plot-specific data. Recent advances in communication and sensor technology now offer workable solutions to these constraints.

The LL addresses environmental, social, and economic dimensions of sustainability through digitalisation, with the following objectives:

- Environmental: reduce water and pesticide use in viticulture; lower CO_2 emissions; minimise vineyard treatments; protect pollinators and support pollination.
- Social: improve time management and enable more sustainable farm business practices.
- Economic: increase profitability of winegrowing and beekeeping enterprises.

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6.2.2 Doppler Winery

The Doppler Winery, located in northern Slovenia, operates under challenging conditions: rugged terrain, highly variable microclimates, and an ongoing transition to organic farming. Under such conditions, conventional weather stations—delivering uniform data for entire farms—are inadequate.

Main challenges

1. Connectivity issues due to the rugged terrain

2. The climate is significantly different in different parts of the vineyard, requiring different responses. Therefore "standard" IoT weather stations that are placed on one location on farm are not suitable for typical Slovenian hilly terrain.

3.The farm is in the process of converting to organic farming. Organic sprays must be applied to the vines as soon as a certain amount of rain falls. Information on the amount of rain at a micro-location is very important.

4. Significant climate change is observed in which the winery has to adopt. More knowledge, information and data is required.

Digital solution adopted

To address these challenges, Doppler Winery deployed a distributed network of IoT sensors instead of relying on a single weather station. The system includes:

- Sensor network: measuring soil moisture, leaf wetness, and rainfall. Sensors use long-life AAA batteries (up to 10 years) and have an average communication range of 15 km.
- Connectivity: data transmission via LoRaWAN (Low-power Wide-Area Network), chosen for its long range, low energy demand, and straightforward configuration. A gateway on a nearby hill transmits data to a server, requiring only Ethernet or Wi-Fi connection.
- Data platform: the open-source ThingsBoard platform, enabling device management, real-time data visualization, API access, and rule-based alerts for vineyard managers. By adopting this digital technologies, the farm expects the following benefits:

Expected benefits

1. Reduction of the use of water and substances in the winegrowing process

2. Saving time for spraying

3. Improve farm profitability through optimised decision-making.

6.3 Environmental impact analysis

6.3.1 Goal and Scope

Goal

The Life Cycle Assessment (LCA) aims to evaluate and compare the environmental impacts of traditional versus digitalised phytosanitary protection in viticulture. It focuses on the potential reductions in CO_2 emissions, pesticide use, and resource consumption (water, fuel, labour time) enabled by IoT-based sensor networks and data-driven decision-making at the Doppler Winery.

The results provide insights for farmers, technology providers, and policymakers into the environmental benefits and trade-offs of digitalisation in organic viticulture, particularly in regions with heterogeneous microclimates..

Scope and functional unit

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- **Case context:** Doppler Winery (northern Slovenia), characterised by rugged topography, variable microclimates, and a transition to organic farming.
- **Functional unit**: "Phytosanitary protection of one hectare of vineyard for one year."

This unit allows for direct comparison between conventional and digitalised practices.

Scenario definition and system boundaries

Two scenarios were defined and compared :

Reference Scenario: Chemical protection of 1 ha of vines under conventional practices. Protection is carried out using a tractor equipped with a spreader, with application frequency and dosage determined by the farm manager based on experience and standard weather data.

Includes the production and application of phytosanitary products, tractor use (fuel, maintenance), and working time. System boundaries cover the vineyard plot and associated farm operations.

Digitalized Scenario: Chemical protection of 1 ha of vines using real-time data from a network of IoT sensors (soil moisture, leaf wetness, rainfall) and a connected weather station. Application frequency and dosage are adapted based on sensor data, aiming to reduce input use and optimize working time.

Includes all elements of the reference scenario, plus the manufacturing, deployment, and operation of IoT sensors, LoRaWAN gateways, data transmission, and platform use (energy, infrastructure). The digital infrastructure's environmental impacts (materials, energy, end-of-life) are accounted for within the system boundaries.

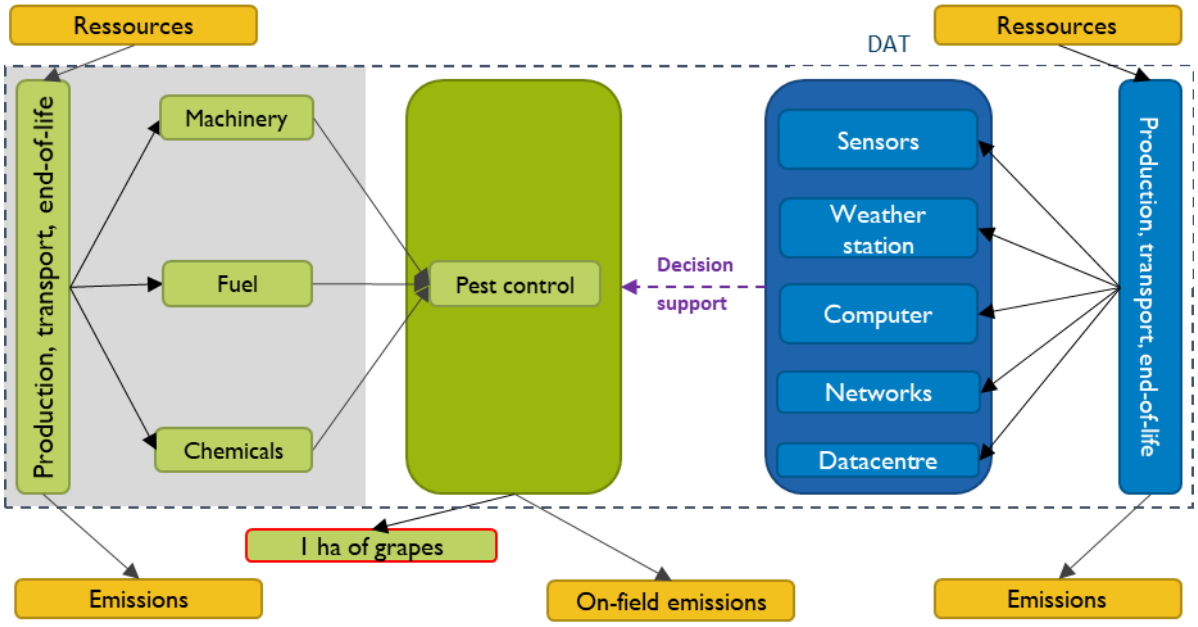

Figure 12: Digitalised scenario system boundaries

6.3.2 Results

After the data inventory phase (LCI), the impact indicators for both scenarios were calculated and analysed in order to be able to answer the following questions :

How does the environmental impacts evolve between the two scenario (before and after digitalisation) ?

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Comparative analysis of the environmental impacts between the reference and digitalized scenarios demonstrates a **systematic reduction in all impact categories** following the adoption and use of digital technologies in the Doppler Winery. As illustrated in Figure 13, the digitalized scenario achieves an **approximate 20% reduction** in impacts across all midpoint categories.

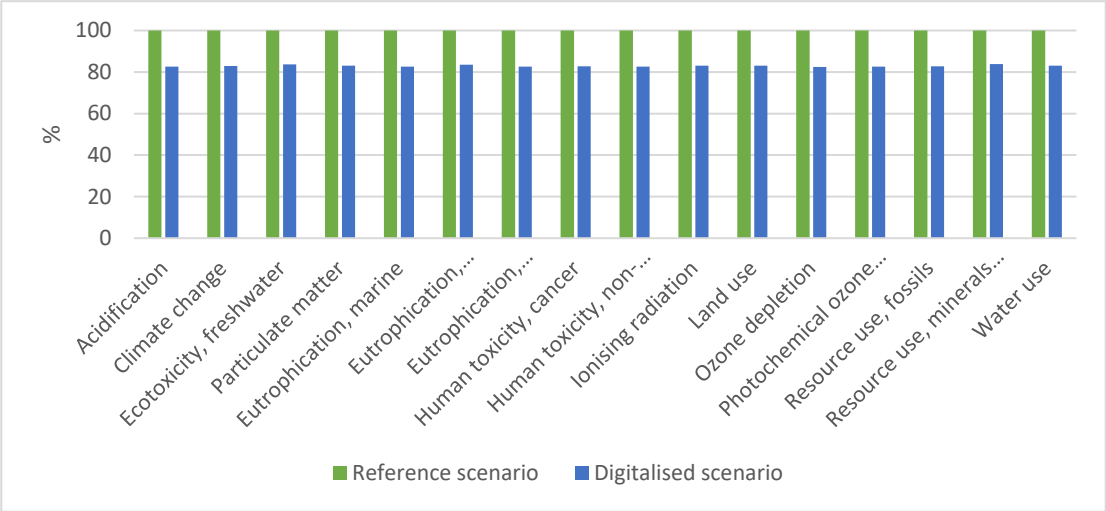

Figure 13: Impacts for the protection strategy of 1ha with and without the use of digital technologies (EF 3.1)

This reduction aligns with previous findings, which identified **chemical application (both production and emissions)** and **diesel consumption for spraying operations** as the primary contributors to the system's environmental burden. The observed decrease in impacts is therefore directly attributable to the **reduced use of phytosanitary products and diesel** in the digitalized scenario. Notably, the **environmental footprint of the digital infrastructure itself**—including sensor manufacturing, data transmission, and platform operation—remains **marginal in comparison**, and thus does not offset the overall environmental benefits achieved through optimized input management.

How does the different process steps contribute to the environmental impacts ?

Figure 14 presents the relative contributions of each process step in the digitalized scenario to the endpoint damage categories—**Human Health, Ecosystem Quality, and Resource Availability**. In the Doppler use-case, the analysis reveals that the most significant environmental impacts arise from **the application of chemical products (both production and field emissions)** and **diesel combustion during spraying operations**. These two processes dominate the overall environmental profile across all endpoint categories.

Regarding the chemicals, the **manufacture of curzate** has a high impact on the system as a whole, but a low impact on emissions in the field, unlike **pepelin**, where the impact of emissions in the field is greater than that of the manufacture of curzate.

Chemicals account for most of the damage to human health, diesel for most of the damage to natural resources, while damage to ecosystems is due to both in similar proportions.

The **manufacture and use of agricultural equipment** has a low impact, while the use of **digital tools** has a very negligible impact.

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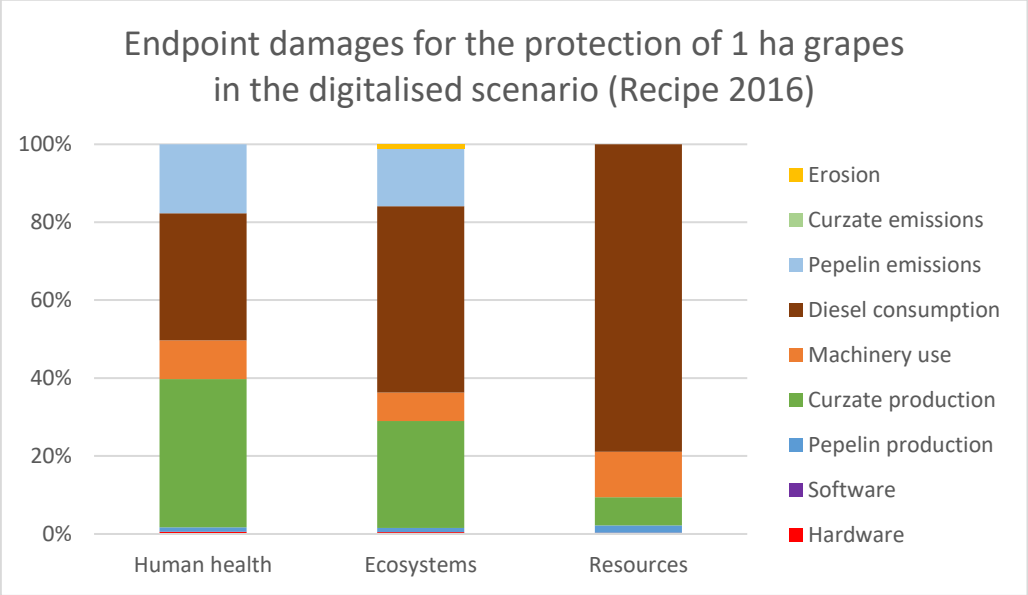

Figure 14 : Endpoint damages for the protection strategy of 1ha of grapes in the digitalised scenario (Recipe 2016)

Midpoint impact characterization of the digitalized scenario (Figure 15) corroborates the endpoint-level findings, revealing a **clear dominance of fuel combustion and curzate production** as the principal environmental hotspots. The contribution of digital infrastructure, however, remains **statistically insignificant** across all impact categories, affirming its marginal role in the overall environmental profile.

Fuel combustion is the leading contributor, responsible for >50% of impacts in Climate Change, Ozone Depletion, and Photochemical Ozone Formation, highlighting its outsized role in atmospheric emissions. **Machinery impacts** are consistently low, except for Ionizing Radiation (~30%), likely linked to material inputs.

Agrochemicals show category-specific dominance: **Curzate** drives ~60% of impacts in Freshwater Eutrophication and Ecotoxicity, due to its copper-based formulation and upstream production burdens. **Pepelin** contributes modestly to Acidification and Particulate Matter, primarily via field emissions rather than manufacturing.

Soil erosion has minimal influence, except for a minor role in Eutrophication from runoff.

Digital infrastructure (sensors, data transmission, platform) adds no significant burden, confirming that optimized input use—not technology adoption—dominates environmental performance. This reinforces the net sustainability benefit of digitalized precision viticulture.

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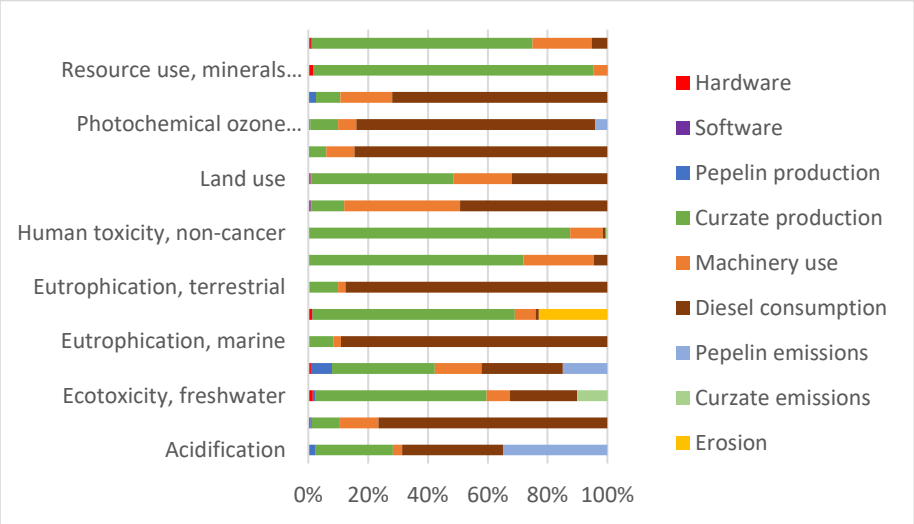

Figure 15 : Impacts for the protection strategy of 1ha of grapes using digital technologies (EF 3.1)

6.3.3 Main messages

This LCA study demonstrates that **diesel consumption** and **agrochemical use**—both from manufacturing processes and field emissions—are the primary drivers of environmental impact in vineyard chemical protection.

The adoption of sensor-based decision support systems, which enable **reduced spraying time** and **optimized input use** without compromising yield, presents a clear opportunity to lower the environmental footprint of phytosanitary treatments.

However, the technology itself—when implemented without corresponding changes in farming practices—**has a negligible effect on overall environmental performance**, whether positive or negative.

These findings are contingent on two key assumptions:

- Yield stability is maintained despite reduced inputs.
- Product quality (particularly for wine grapes) remains unaffected by the shift in management practices.

This underscores the critical role of practice adaptation in realizing the sustainability potential of digital tools in viticulture.

6.4 Economic C&B analysis

6.4.1 Methodology and data collection

The economic analysis of the Doppler Winery follows the CODECS multi-step, data-driven methodology, tailored to assess the costs and benefits of adopting digital technologies in agriculture. This analysis includes: (i) A basic economic analysis (qualitative and quantitative based on a web survey), (ii) a Budget analysis (partial budget table), and (iii) the Net Present Value (NPV) analysis (profitability and risk assessment).

To estimate the economic costs and benefits, the Slovenian LL responded to both the online questionnaire and on the face-to-face in depth survey registering the data for the Doppler Winery. Additional clarifications were provided by email, after the research team contacted the coordinators.

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6.4.2 Result of the basic economic analysis

Initial investment costs

The initial investment costs basically account for the acquisition of the technology, since no additional installment costs or software costs were reported. Also, no transaction costs are reported in the case of the Doppler Winery.

This may be explained by the fact that the technology is established within the CODECS project, and thus some services are provided to the Doppler Winery cost-free. For example, there are no information seeking or additional training costs for the managers of the winery.

6.4.3 Result of the Budget Analysis

The effect that the adoption of the digital solution has on the costs and revenue items of the Doppler winery can be summarized as following:

- The workload and the inputs (i.e. energy, water, consumables) decreased.
- The only additional cost reported is related to the use of the digital technology.
- No annual costs for training, licenses, legal representation etc. were required
- The quantity and quality of the production is expected to increase, though currently the exact estimations cannot be provided.
- The market risk is expected to decrease, probably due to a more consistent quantity and quality of the production.

As can be seen the result of the analysis is positive since the reduced costs exceed the additional costs. It should be emphasized that the positive result of the analysis maybe underestimated because no additional income is included from the anticipated increase in yield and in quality of the produce.

We should also emphasize that, some cost savings derived from the reduction in the usage of some machines like the tractor and the sprayer may occur but were not included in the analysis. For example, the depreciation cost of the tractor and sprayer is normally considered a fixed cost (spread over years regardless of use). But digitalisation may extend the useful life of the machine in which case the annual depreciation cost may decrease.

However, we do not consider this drop in depreciation costs, since the machinery is already owned and depreciated on the books. Accordingly, some part of annual maintenance costs (e.g. lubricant changes) are usage-dependent, but another part like annual inspection may not depend on the use. Therefore, all annual cost savings of this kind were considered fixed “with”and “without” the digital technology

Costs Savings

Reduction in operational costs:

- Lower workload and labour requirement
- Decrease of inputs: Phytosanitary products, Energy, Water
- Improved efficiency : digital tools optimised resource management

Expected benefits: Increased production (quantity / quality), reduced market risk

Additional Costs

Depreciation

Maintenance

Insurance for the digital technology

Positive Net Impact

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Figure 16 Summary of the Budget Analysis of the Doppler Winery (SLO) use-case

6.4.4 Result of the NPV analysis

The results of the **Net Present Value** (NPV) analysis also demonstrate that the investment in the digital technology adopted is profitable for the Doppler Winery. The NPV value assuming a 7% discount rate-which is higher than the current long-term interest rate in Slovenia- and a 7 year life-span of the investment, is positive and generates positive cash flows for all years after year 0 (see also the cash flow chart, Figure 17: Cash flow chart of the investment), because the initial investment cost was included in year 0. Also the interest costs are not considered in the NPV analysis.

It should also be emphasized that even if a higher discount rate is used to account for economic risk and uncertainty (sensitivity analysis of the discount rate) the NPV value remains positive, as can be seen in the NPV graph (Figure 18). Only if a discount rate higher than 40% is used the NPV turns negative, which indicates a very safe investment.

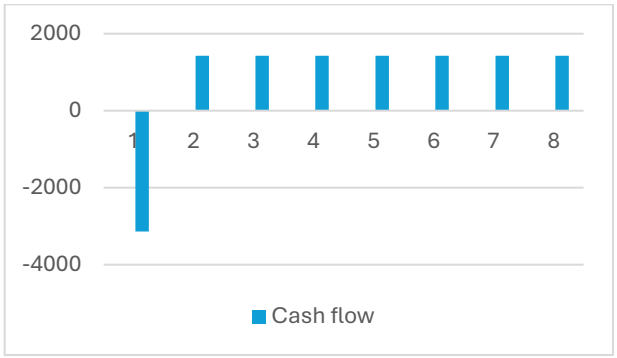

Figure 17: Cash flow chart of the investment

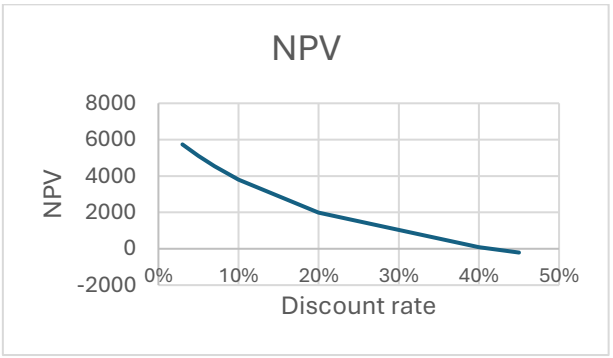

Figure 18 : NPV of the investment across various discount rates

Though stochastic analysis is not possible in the case study of the Doppler Winery (production and price fluctuations are not reported), scenario analysis can be performed if relevant. Increased yield or price scenario can be tested, but it is not required since the investment is profitable even with no increase in yields or prices. Many public funding options are also available in Slovenia, but for the same reason as in the yield and price scenario, public funding scenario is not examined either.

A smaller life span of the investment was however used, to account for the obsolescence of digital technologies. The NPV, though smaller is still positive when a 5-year life span is used as shown in Figure 19.

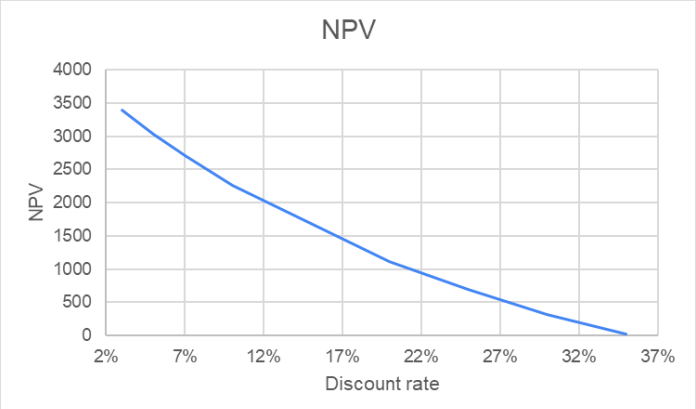

Figure 19: NPV of the investment across various discount rates, using a 5-year life span

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6.4.5 Main messages

The Doppler Winery's investment in the digital technologies proves to be a low-risk, high-reward investment, delivering immediate cost savings and operational. While current results show resilient profitability and reduced resource use, the full potential—including revenue growth from improved yield and quality—remains to be quantified as more data becomes available.

6.5 Social/Human Costs and Benefits analysis

6.5.1 Methodology and data collection

The digitalisation of agriculture, understood as the integration and use of digital technologies into everyday farming practices, generates a complex and ambivalent reality for farmers, shaping their lived experiences, work organisation, and social interactions. To capture the perspective of the farmers at the Doppler Winery, a semi-structured interview was conducted and analysed in conjunction with 23 additional interviews from the different CODECS Living Labs. The resulting material was structured around three overarching themes: human wellbeing, work organisation, and social integration. Each theme was further divided into two categories - costs and benefits - in order to reflect both the positive and negative dimensions of digitalisation. Within these categories, more specific subcategories were defined to provide a nuanced account of the findings. The next section present key findings on human costs and benefits for farmers at Doppler Winery.

6.5.2 Results

The sunburst diagram (Figure 20) captures the lived human impacts of the IoT monitoring system at the Doppler Winery. Only the full-colour categories were observed, while light-coloured ones were not part of the experience.

Human Benefits

The IoT system **strengthens decision-making** by acting as a "decision support tool" that provides daily data on rainfall, humidity, and temperature and issues alerts when thresholds are exceeded. This enables informed choices and targeted interventions. It **enhances knowledge and understanding**, as farmers "*know what is happening at each location*" and can respond effectively in emergencies. The system also contributes to **well-being** by reducing unnecessary vineyard inspections, **saving time**, and **lowering physical strain and exposure to chemicals**.

Work Benefits

At the operational level, the system **improves planning and management** by aligning tasks with real-time conditions and reducing unnecessary spraying. Beyond efficiency, the reduction of chemical inputs supports ethical and sustainable farming practices, **reinforcing the farmers' values** and contributing to their **sense of pride** and **job satisfaction**. These practices also underpin the farm's pursuit of eco-certification and strengthen its reputation for producing clean and high-quality wines.

Work Costs

The only drawback reported was the **operational burden** and **added complexity of integrating sensor data into daily routines** ("*Experiencing problems of connectivity on the fields*")

Other potential risks such as mental stress, workforce reduction, or financial strain were not observed.

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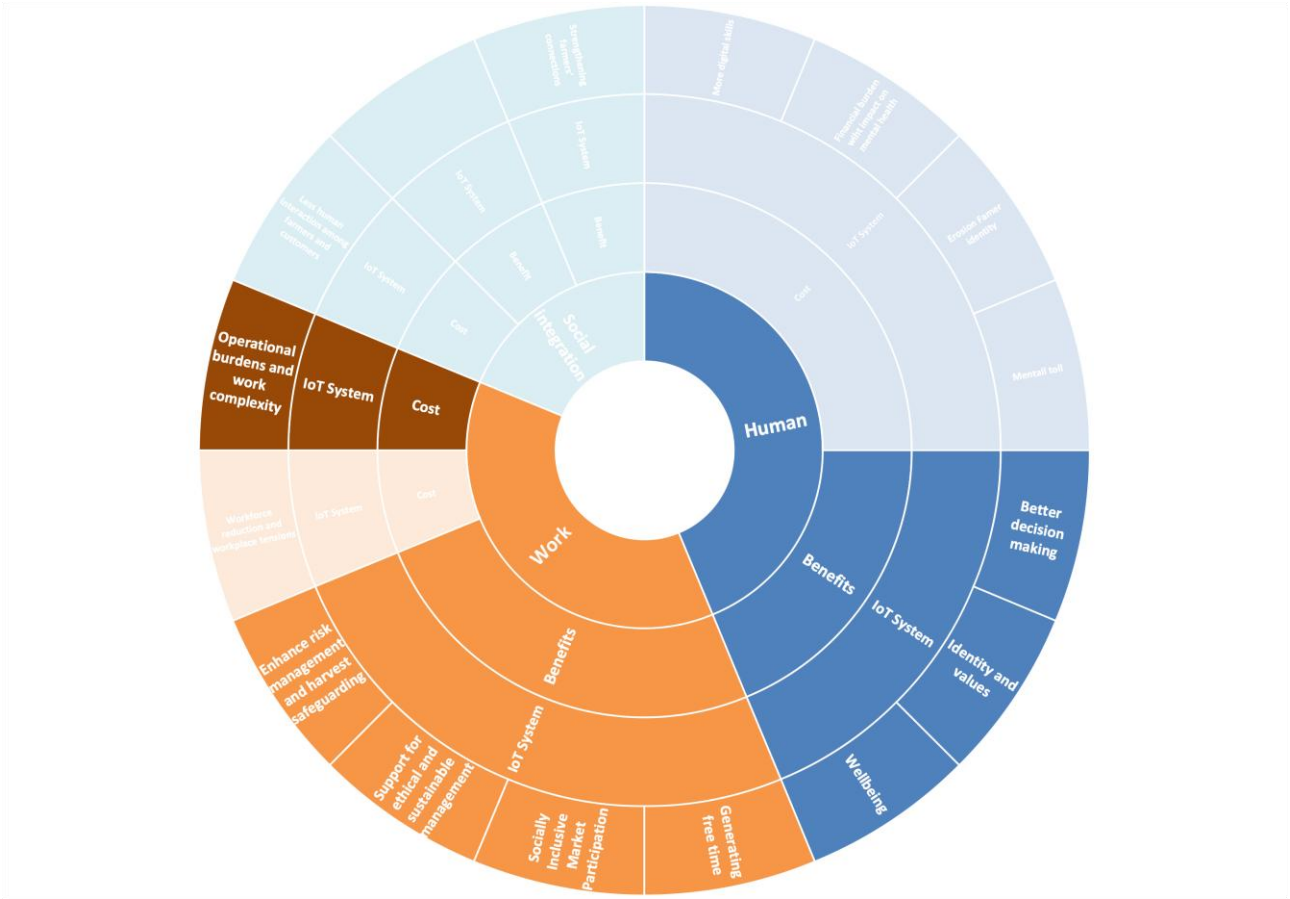

Figure 20 Human centred cost and benefits of farm digitalisation in the Slovenian LL (Smart Villages Network)

6.5.3 Main messages

Overall, the Doppler Winery's lived experience demonstrates that IoT monitoring delivers substantial human and work-related benefits by improving planning, knowledge, well-being, and alignment with ethical and sustainable values, while introducing only one manageable cost.

The Doppler Winery case shows a focused set of lived of human imapcts from IoT monitoring, with benefits in decision-making, knowledge, well-being, and sustainable practices, and only one cost linked to operational burden. The broader diagram, however, includes categories associated with other digital technologies and farming contexts, where issues such as financial strain, mental stress, workforce reduction, or workplace tensions have been reported. This contrast underlines that the Doppler experience reflects the specific role of IoT monitoring rather than the full range of digitalisation impacts in agriculture.This contrast underlines that the Doppler experience reflects the specific role of IoT monitoring rather than the full range of digitalisation impacts in agriculture.

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7 Conclusion

Authors : Alexia Gobrecht (INRAE)

This deliverable consolidates the first assessment of the Costs and Benefits of farm digitalisation within CODECS. The results demonstrate that digital technologies can deliver tangible advantages in terms of resource efficiency, profitability and farmer's well-being, but they also generate new costs and risks, including financial burden, dependency on providers, increasing energy use and governance challenges.

Across environmental, economic, and social analyses, a nuanced picture emerges: efficiency gains and reduced environmental impacts are not guaranteed and often depend on context-specific factors such as farm size, crop systems, and digital maturity. Economic assessments confirm that profitability is possible but contingent on upfront investment and learning costs. Human-centred studies highlight that digitalisation reshapes farmers' identities, values and work organisation as much as their economic performance.

A key lesson is that digitalisation should not be viewed as a purely technical pathway to sustainability but as a socio-technical transition requiring careful governance, inclusive dialogue, and transparent evaluation. Returning outputs and feedback to Living Labs and their stakeholders is essential, both to ensure the relevance of analyses and to foster trust and adoption in practice.

Going forward, WP4 will continue to analyse the environmental, economic, and social costs and benefits in the LL, while also working towards a more holistic perspective. The aim is to link findings across dimensions to reveal trade-offs and synergies in a pragmatic way. This approach will provide stakeholders with evidence that is both robust in each dimension and meaningful when considered together, thereby supporting decisions that align digitalisation with the long-term sustainability of European agriculture.

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8 Supplementary material

8.1 On-line questionnaire for Economic C&B analysis

The first level of the methodological framework for the economic C&B analysis, as shown in Figure 8, involves a qualitative analysis, particularly in cases where farm data are limited. This step can be applied to all Living Labs (LLs), including those that have not yet begun digitalizing, as it requires minimal quantitative information. The goal of this phase is to identify potential economic costs and benefits, even when quantitative farm data are unavailable or difficult to estimate.

Table 3 presents an indicative questionnaire designed for this purpose. The questionnaire is concise and easy to complete, focusing on key questions related to transition and operational costs and benefits. It has been developed based on existing literature and the D2.1 CODECS Conceptual Framework, which outlines the types of costs and benefits associated with the adoption of digital technologies.

The required data can be collected by LL coordinators or completed directly by farmers using an online questionnaire. In some cases, additional data may be available from other tasks within the CODECS project. The research team will finalize the questionnaire's format and determine the timeline for this initial data collection phase, which will run in parallel with Task 4.3 (Environmental Analysis).

If quantitative data are limited for certain LLs, only preliminary qualitative data on economic costs and benefits will be presented as case studies. As a result, this basic economic analysis will complement the more detailed findings gathered from in-depth interviews.

Table 3: Indicative questionnaire for the preliminary data collection and economic analysis

Questions
1. What is the size of your farm ?
2. Is the investment in the digital technology annual or multiannual? / Do all investment costs occur during the first year?
3. How much is the initial investment cost for acquiring the technology?
4. What is the productive life of the investment (i.e. in how many years does the equipment need to be replaced?).
5. If part of the investment needs to be replaced after a few years, when does it need to be replaced and how much does this cost?
6. Does the new technology require any software? If yes, how much does the software cost? Is it a lump sum payment or annual payment?
7. Does the technology require extra labour cost for its establishment?
8. Does the establishment of the technology require adjustments of the existing farm infrastructure (e.g., land improvements)? What is the cost of these adjustments?
9. Does the use of the technology require special license? How much is the cost of this license? Is this a lump sum payment or annual?
10. Does the use of the technology require training of farmer/workers or contract labour of specialized workers? How much is the cost of training or contract labour? Is this a lump sum payment or annual?
11. Does the use of the technology require the use of special consumables? How much is the annual cost of these consumables?
12. Is the use of the technology expected to affect the labour requirements in the farm? Are labour costs expected to increase or decrease and how much?
13. Is the use of the technology expected to affect the cost of consumables of the farm (e.g.fertilizer or pestcide costs)? Are these costs expected to increase or decrease and how much?

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14. Is the use of the technology expected to affect the cost of water consumption or/and the cost of energy consumption? Are these costs expected to increase or decrease and how much?
15. Is the use of the technology expected to affect the quantity produced? How much?
16. Is the use of the technology expected to affect the quality of the product? Will this reflect on product price increase or decrease? How much?
17. Will there be any other changes on production costs or revenues that has not been mentioned in the previous questions?

Access to on-line questionnaire here

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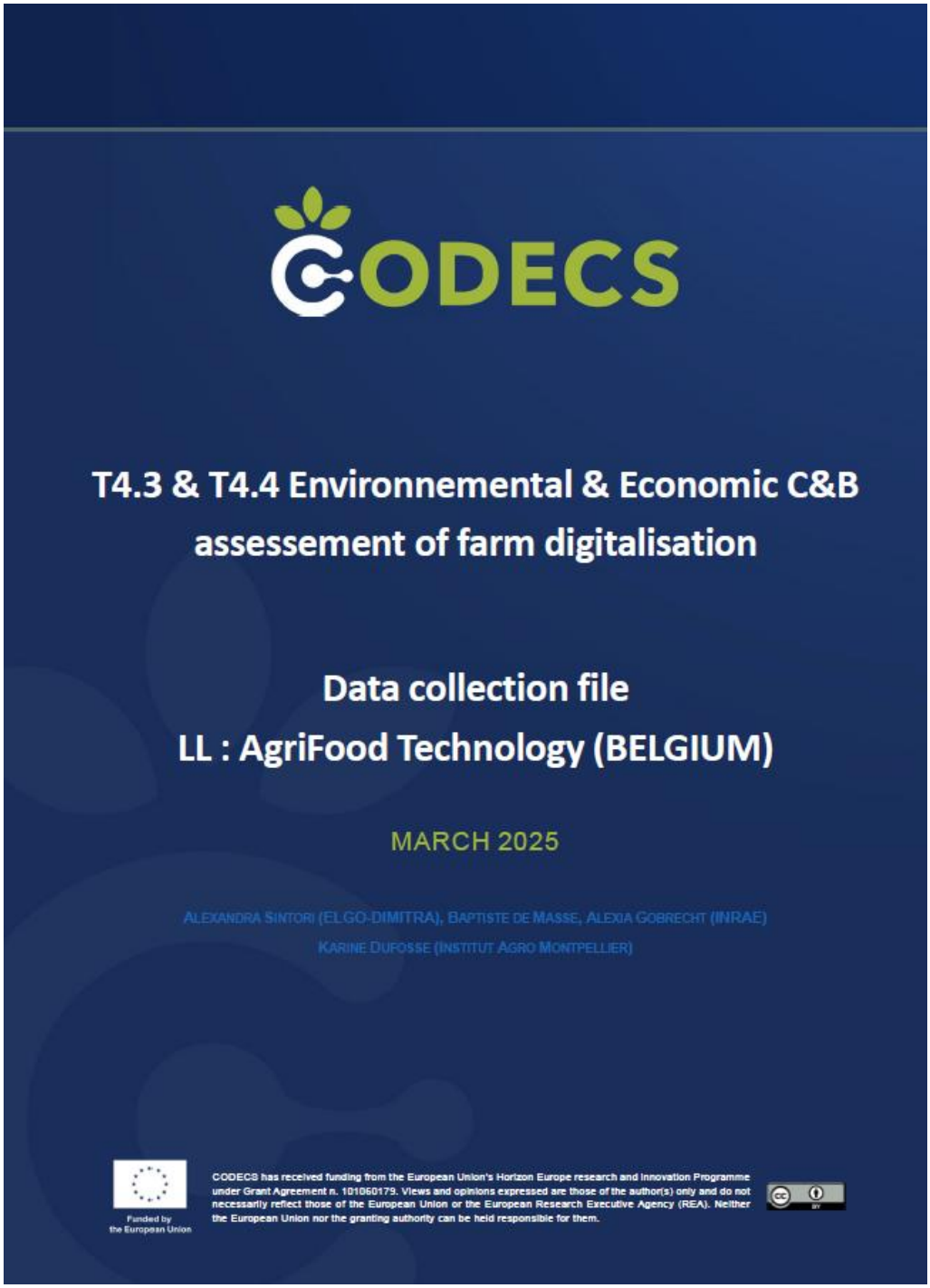
8.2 Example of a Data Collection File for the in-depth interview

The data collection files for the LL have been prepared for each LL according to their specificities (type of production, system boundaries, type of digital technologies). The data collection file is available in Excel format and also in Pdf.

Here some snapshots of the document which can also be found here.



Economic Costs and Benefits & Environmental impact analysis of farm digitalisation			
NAME OF THE LIVING LAB :	AgriFood Technology	COUNTRY :	BELGIUM
LL COORDINATOR:	ILVO	CONTACT :	*please insert contact name*
PROBLEM STATEMENT	*The AgriFood Technology LL wants to develop tools to reduce the use of plant protection products by spraying more precisely through the use of ultra-high resolution RGB images on drones and AI models, task map generation tools and label tools for weeds, diseases and pest detection of arable crops.*		
DIGITAL TECHNOLOGIES	*Ultra-high resolution RGB imagery obtained from drone, use of tools of task map generation and label to detect pests, weeds and diseases, RTK positioning, Variable Rate Application*		
MAIN PRODCUTION	*Potatoes*		

INTRODUCTION

Data Collection File for Evaluating the Costs and Benefits of Digitalization at the Farm Level in Your Living Lab

This document is designed to help you collect the necessary data for both environmental impact assessments and economic cost-benefit analyses. You can either print and fill out the document manually or enter the data directly into the Excel file, although, in the excel file, it is easier to add lines.

Document and the excel file are organized as follows:

- CONSENT FORM tab : which you can prepare or adapt before the interview with the farmer.
- REFERENCE SCENARIO tab: Outlines the steps of the agricultural process ***before*** *the implementation of digital technology.*
- DIGITAL SCENARIO tab: Details the steps of the agricultural process ***after*** *the implementation of digital technology.*
- DIGITAL TECHNOLOGY tab: Provides a breakdown of the different components of the digital technology, their uses and investement costs.
- OTHER ECONOMIC DATA tab: Collects additional economic data at the farm level.

Throughout the file, blue italicized text provides instructions and examples to guide you in completing each section. A ***Comments*** *column is available for adding details, noting uncertainties, or sharing any other relevant information.*

As Living Lab coordinator, we suggest you to start by entering all the information you already have. If needed, you can then consult the farmer or farm manager to complete the missing data. If so, you may also record the interview with the farmer to refer back to it later for data entry. However, translating or transcribing the interview is not required.

Some sections require details about equipment or products used. If it's easier, you can take photos of the equipment, tools, and product datasheets and send them to us.
We will extract the necessary technical information ourselves.

If possible, request logbook extracts or crop monitoring sheets, as they may help with data entry.

Once the data collection is complete, please enter the information into the Excel file and send it back to us (Alexia.gobrecht@inrae.fr and sintori@elgo.gr)

Off course, we are available to answer your questions if you have some doubts regarding the process.

Thanks a lot for your commitment.

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REFERENCE SCENARIO

REFERENCE SCENARIO

NAME OF THE LIVING LAB : AgriFood Technology COUNTRY : BELGIUM

The reference scenario refers to the agricultural process to produce **1 Ha of potatoes** in the ILVO Farm before the introduction of the set of digital technologies.

Comments : *you can add comment in this frame, about the data collection, for example, which year of production is concerned, the source of data (from the farm directly, estimated etc...), all what you seem relevant to know about the process.*

SECTION 1 TILLAGE *Refers to the soil preparation practices. Please fill in one practice per line. You can add lines if you need. Important to specify the data in the right unit*

Type of practice	Dates of practice	Tractor used (or main machine)		Tool used (secondary machine)		Energy source	Quantity of energy used	Price of energy (€/unit)	Labour required (hours/ha)		Wage (€/hour)	Cost contract labour (€/ha)	Comments
		Type and brand	Duration (hours/ha)	Type (Name or function)	Duration (hours/ha)	Diesel, gas, electricity, etc	L or kWh/ ha		Family	Paid			
Exemple: Ploughing	*10/10/2024*	*Fendt 500*	*1*	*Plough Lemken Juwel 7*	*1*	*Diesel*	*40L*	*1.8€/L*	*1*	*0*	*0*	*0*	
Tillage 1													
Tillage 2													
Add lines if necessary													

SECTION 2 SEEDING *Refers to the seeding practice. Important to specify the data in the right unit*

Type of practice	Dates of practice	Tractor used (or main machine)		Tool used (secondary machine)		Energy source	Quantity of energy used	Price of energy (€/unit)	Labour required (hours/ha)		Wage (€/hour)	Cost contract labour (€/ha)	Input type	Quantity (unit/ ha)	Price (€/unit)	Comments
		Type and brand	Duration (hours/ha)	Type (Name or function)	Duration (hours/ha)	Diesel, gas, electricity, etc	L or kWh/ ha		Family	Paid						
exemple	*10/11/2024*	*Fendt 500*	*2*	*Seeder Kuhn Aurock 600*	*2*	*Diesel*	*40L*	*1.8€/L*	*0*	*2*	*10*	*20*	*Barley seeds*	*150 kg*	*1*	
seeding 1 potato																
...																

DIGITAL SCENARIO

DIGITAL SCENARIO

NAME OF THE LIVING LAB : AgriFood Technology COUNTRY : BELGIUM

The digital scenario refers to the agricultural process to produce **1 Ha of potatoes** in the ILVO Farm after the introduction of the set of digital technologies.

Comments : *you can add comment in this frame, about the data collection, for example, which year of production is concerned, the source of data (from the farm directly, estimated etc...), all what you seem relevant to know about the process.*

SECTION 1 TILLAGE *Refers to the soil preparation practices. Please fill in one practice per line. You can add lines if you need. Important to specify the data in the right unit*

Type of practice	Dates of practice	Tractor used (or main machine)		Tool used (secondary machine)		Energy source	Quantity of energy used	Price of energy (€/unit)	Labour required (hours/ha)		Wage (€/hour)	Cost contract labour (€/ha)	Comments	
		Type and brand	Duration (hours/ha)	Type (Name or function)	Duration (hours/ha)	Diesel, gas, electricity, etc	L or kWh/ ha		Family	Paid				
Exemple: Ploughing	*10/10/2024*	*Fendt 500*	*1*	*Plough Lemken Juwel 7*	*1*	*Diesel*	*40L*	*1.8€/L*	*1*	*0*	*0*	*0*		
Tillage 1														
Tillage 2														
Add lines if necessary														

SECTION 2 SEEDING *Refers to the seeding practice. Important to specify the data in the right unit*

Type of practice	Dates of practice	Tractor used (or main machine)		Tool used (secondary machine)		Energy source	Quantity of energy used	Price of energy (€/unit)	Labour required (hours/ha)		Wage (€/hour)	Cost contract labour (€/ha)	Input type	Quantity (unit/ ha)	Price (€/unit)	Comments
		Type and brand	Duration (hours/ha)	Type (Name or function)	Duration (hours/ha)	Diesel, gas, electricity, etc	L or kWh/ ha		Family	Paid						
exemple	*10/11/2024*	*Fendt 500*	*2*	*Seeder Kuhn Aurock 600*	*2*	*Diesel*	*40L*	*1.8€/L*	*0*	*2*	*10*	*20*	*Barley seeds*	*150 kg*	*1*	
seeding 1 potato																
...																

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DIGITAL TECHNOLOGIES

DIGITAL TECHNOLOGIES IMPLEMENTED IN THE LIVING LAB

NAME OF THE LIVING LAB : AgriFood Technology COUNTRY : BELGIUM

This section is dedicated to the digital technologies implemented in the Living Lab. We prefilled the table with the different components of the set of digital technologies used, according the docment you transferred us. Feel free to correct and complete these information.

Comments : *you can add comment in this frame, about the data collection, for example, which year of production is concerned, the source of data (from the farm directly, estimated etc...), all what you seem relevant to know about the process.*

SECTION 1 INVESTMENTS REQUIRED FOR DIGITAL TECHNOLOGIES *Refers to the all the digital tools (software and hardware) used and the investments needed for their use*

Is the investment annual or multiannual ? Annual *yes/no* Multiannual *yes/no*
How many years does the establishment of the investment last ? years

If the investment is multiannual, please copy past the table below and fill it in for each investment year.
One component per line. If you have 3 times the same component, you can indicate it in the comments.

Investments in Year 1										
Type investment *(e.g. type of equipment)*	Characteristics/ description	Purchase price as new (€)	Annual subscription (€/year)	Replacement rate *(e.g. every 2 years)*	Annual insurance or maintenance costs *(€)*	Percentage of use on the farm *(% of surface)*	Annual Operating Hours (hours/year)	Duration of use specifically for digitalized scenario (h/ha)	Cost of other investments	Comments
exemple	*Hygrometry sensor*	*20*	*0*	*every 5 years*	*0*	*100*	*24*365 = 8760*	*8760*		*3 sensors in the farm*
DRONE DJI M600										
DRONE DJI M350										
Raspberry pi 5B										
GPS Septentrio										
RTK antenna 1										
RTK antenna 2										
Netgear router										

OTHER ECONOMIC DATA

ECONOMIC INFORMATION

NAME OF THE LIVING LAB : AgriFood Technology COUNTRY : BELGIUM

This section is dedicated to the informations that are specific to economics.

Comments : *you can add comment in this frame, about the data collection, for example, which year of production is concerned, the source of data (from the farm directly, estimated etc...), all what you seem relevant to know about the process.*

SECTION 1 FIXED CAPITAL *Refers to the all the physical assests (machinery, tools, infrastructures, etc) that are used in the production process concerned by the use of the digital technology*

	Type	Characteristics	Year of purchase	Purchase price (as new) (€)	Percentage of use on the farm *(%)*	Annual Operating Hours (hours/year)	Annual rent to other farms *(€)*	Maintenance *(€/year)*	Insurance *(€/year)*	Use in potatoes before the DT *(%)*	Use in potatoes after the DT* *(%)*
exemple	*Tractor*	*Fendt 500*	*2017*	*80000*	*30*	*400*	*0*	*2000*	*1000*	*100*	*100*
Transport											
Tractor											
Other tools											
Irrigation											
Harvest											
Other											

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8.3 Practice Abstract of the Slovenian Use-Case

1. Objectives and general approach

Farm digitalisation, considered as the adoption and use of digital technologies in farming systems, transforms, in a positive or negative way; a large number of components of the system. The objective of the work carried out in WP4 of the CODECS project is to capture these changes to analyse the environmental, economic and social costs and benefits of the digitalisation of agriculture.

This document summarizes the results of the costs and benefits analysis on a use-case in the Slovenian SVN Living Lab.

Smart Villages Network Living Lab
Slovenia

Authors

Alexia Gobrecht (INRAE), Alexandra Sintori (Elgo-Dimitra), Mauro Florez (INRAE)

Anticipated users of the Practice Abstract

Farmers, Advisors, Public authorities

More info:

www.horizoncodecs.eu/farm/doppler-winery-hisa-vina-doppler/

2. Description of the LL and use-case

The Smart Villages Network is a Living Lab located in Slovenia, in three different regions from west to east of the country. It connects farmers, researchers, technology providers, and government representatives. The LL focus on the use of digital technologies in viticulture in order to improve social, economic and environmental sustainability, with the main objectives of lowering CO_2 emissions and pesticides use, improve time management, and farm profitability.

The Doppler Winer, Maribor, Slovenia has been digitalised since 2010 and is in the process of converting to organic farming. It faces challenges with rugged terrain, poor connectivity, and significant microclimate variations across its vineyard, which makes standard, single-location weather stations unsuitable. The winery needed a solution to get precise, micro-location data, especially rainfall information, to apply organic sprays promptly and adapt to climate change.

The implemented digital technology is a **vineyard monitoring system that uses a network of dispersed IoT sensors** to measure soil moisture, rain, and leaf wetness. This system utilizes **LoRaWAN technology for long-range, low-power communication** between the sensors and a gateway. Data is aggregated on the **ThingsBoard open-source platform**, which can be used to visualize data and create alarms to support the farmer's decisions. A mobile application is also being developed to work with this system.

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3. Environmental analysis

3.1. Methodology

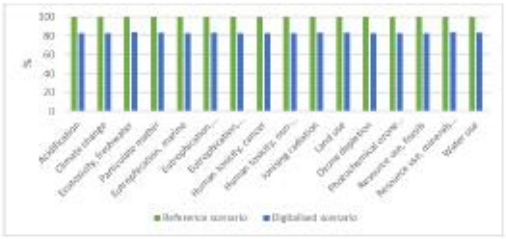
Comparative Life Cycle Assessment (LCA) is a method used to evaluate and compare the environmental impacts of two alternative systems — in this case, the same farming process before and after digitalisation — by quantifying changes in resource use, emissions, and environmental damage across the entire life cycle. This approach helps identify whether and how digital technologies contribute to reducing the environmental footprint of agricultural practices.
For this use-case, the comparison involves:

- A **reference scenario**: plant protection of 1 Ha of vines under conventional practices (without the use of information from IoT sensors.)
- A **digitalised scenario**: plant protection of 1 Ha of vines using real-time data from a network of IoT sensors and a connected weather station, allowing optimized decisions.

3.2. Results

How does the environmental impacts evolve between the 2 scenarios?

By comparing the two scenario (before and after technology adoption), there is a systematic reduction of the environmental impacts across all the impact categories (around 20 %) for the digital scenario.

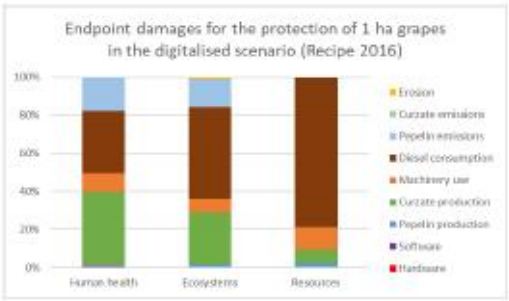


How does the different process steps contribute to the environmental impacts?

Resource damages are overwhelmingly driven by diesel consumption, making energy use the key hotspot.

Human health & ecosystems impacts stem from a mix of diesel use, pesticide production (curzate, pepelin), and field emissions.

Digitalisation (hardware/software) contributes marginally to impacts compared to conventional inputs.



3.3. Main message

In the Doppler Winery use-case, environmental impacts are primarily driven by the plant protection inputs and diesel consumption, whereas the direct contribution of digital components (hardware and software) remains limited. Nonetheless, the real-time information enabled by the sensor network plays a crucial role in guiding strategic input management, thereby fostering reductions in both pesticide use and fuel consumption.

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4. Economic analysis

4.1. Methodology

The economic analysis of the Doppler Winery follows the CODECS **multi-step, data-driven methodology**, tailored to assess the costs and benefits of adopting digital technologies in agriculture. This analysis includes: (i) A basic economic analysis (qualitative and quantitative based on a web survey), (ii) a Budget analysis (partial budget table), and (iii) the Net Present Value (NPV) analysis (profitability and risk assessment).

4.2. Results

Initial Investment :

- The winery's investment focused **exclusively on capital costs** for digital technology, including IoT sensors, communication hardware, and data infrastructure.
- **No additional intangible costs** (e.g., training, permits, legal costs)

Budget Analysis:

Costs Savings	Additional Costs
Reduction in operational costs : • **Lower workload and labour requirement** • **Decrease of inputs : Phytosanitary products, Energy, Water** • **Improved efficiency : digital tools optimised resource management**	Depreciation Maintenance Insurance for the digital technology

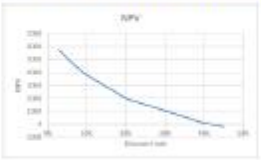
Positive Net Impact

Expected benefits: Increased production (quantity / quality), reduced market risk

Profitability Analysis :

Positive Cashflow **from the first year**

Positive Net Present Value **(NPV) across varying economic conditions (here variable discount rates)**



4.3. Main messages

The Doppler Winery's investment in the digital technologies proves to be a **low-risk, high-reward investment**, delivering immediate cost savings and operational. While current results show **resilient profitability and reduced resource use**, the full potential—including revenue growth from improved yield and quality—remains to be quantified as more data becomes available.

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5. Social Cost & Benefits analysis

5.1. Methodology

The digitalisation of agriculture, understood as the integration and use of digital technologies into everyday farming practices, generates a complex and ambivalent reality for farmers, shaping their lived experiences, work organisation, and social interactions. To capture the perspective of the farmers at the Doppler Winery, a semi-structured interview was conducted and analysed in conjunction with 23 additional interviews from the different CODECS Living Labs. The resulting material was structured around three overarching themes: **human wellbeing**, **work organisation**, and **social integration**. Each theme was further divided into two categories - costs and benefits - in order to reflect both the positive and negative dimensions of digitalisation. Within these categories, more specific subcategories were defined to provide a nuanced account of the findings. The next section present key findings on human costs and benefits for farmers at Doppler Winery.

5.2. Results

The sunburst diagram illustrates the lived human impacts of the use of the IoT monitoring system at the Doppler Winery. Only the full-colour categories were observed in practice, while the light-coloured ones (resulting from the global analysis) were not reported by Doppler Winery farmers, but apprear in the overall CODECS analysis.

Better decision making

"on a daily basis, we check data form the dashboard to plan the activities in the vineyard, to perform treatments in the vineyard, only if and where necessary" ;

"better planning and management of farm activities" ;

"We do have sufficient technical knowledge. You and other teams are always available for advice"

Well being

"Sensors are installed in the cellar for safety against carbon dioxide. The cellar is fingerprint protected. In the event of too high CO_2 content, entry is prevented "

Support for Ethical and Sustainable Management

"It is very eco-friendly to know your vineyards properly"

Operational Burden

"to find best IoT infrastructure for winemakers that would solve current problems with connectivity and very rugged territory with different microclimate in same vineyard"

5.3. Main messages

The Doppler Winery case shows a focused set of lived of human imapcts from IoT monitoring, with benefits in decision-making, knowledge, well-being, and sustainable practices, and only one cost linked to operational burden. The broader diagram, however, includes categories associated with other digital technologies and farming contexts, where issues such as financial strain, mental stress, workforce reduction, or workplace tensions have been reported. This contrast underlines that the Doppler experience reflects the specific role of IoT monitoring rather than the full range of digitalisation impacts in agriculture.

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