SUSTAINABLE DIGITALISATION: A CONCEPTUAL FRAMEWORK

16 SEPTEMBER 2024

KATRINE SOMA (WR), GIANLUCA BRUNORI (UNIPI), CYNTHIA GIAGNOCAVO (UAL), ANDREA KNIERIM (UHOH), DANIELE VERGAMINI (UNIPI), ROSA MARIA HEREDIA HORTIGÜELA (UAL), ALESSIO FERRARI (CNR), CHIARA MANNARI (CNR), MANLIO BACCO (CNR), TROND SELNES (WR), ELISA CIRAVEGNA (WR), LIVIA ORTOLANI, (UNIPI), REINOUT GODAERT (ILVO), MARK RYAN (WR)

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them

CC BY

D2.1 SUSTAINABLE DIGITALISATION: A CONCEPTUAL FRAMEWORK

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	www.horizoncodecs.eu
Document Type	Deliverable
File Name	D2.1. SUSTAINABLE DIGITALISATION: A CONCEPTUAL FRAMEWORK
Status	Final
Dissemination level	Public
Date of creation	16.09.2024
Keywords	Sustainable digitalisation, farmer needs, digitisation, digitalisation, societal transition, system thinking, environmental, social and economic costs & benefits, long term perspective, business processes, digital ecosystem, socio-cyber-physical system
Authors	Katrine Soma (WR), Gianluca Brunori (UNIPI), Cynthia Giagnocavo (UAL), Andrea Knierim (UHOH), Daniele Vergamini (UNIPI), Rosa Maria Heredia Hortigüela (UAL), Alessio Ferrari (CNR), Chiara Mannari (CNR), Manlio Bacco (CNR), Trond Selnes (WR), Elisa Ciravegna (WR), Livia Ortolani (UNIPI), Reinout Godaert (ILVO), Mark Ryan (WR)
Reviewers	Gianluca Brunori (UNIPI), Tiziana Nadalutti (UNIPI)
Version n.	2
Following updates	
Work package	WP2 – Stichting Wageningen Research (WR)
Task number and title	T 2.1 Co-development of conceptual framework
Work Package Leader	WP2 – Katrine Soma (WR)
Contributors	All partners
Project Coordinator	University of Pisa

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

This license enables reusers to distribute, remix, adapt, and build upon the material in any medium or format, so long as attribution is given to the creator

.

SUSTAINABLE DIGITALISATION: A CONCEPTUAL FRAMEWORK (VERSION 2.0)

History of changes			
Version	**Date**	**Changes**	**Authors(s)**
0.1	15 January	First draft	Katrine Soma (WR), Gianluca Brunori (UNIPI)
0.2	15 March	Internal Review	Katrine Soma (WR), Gianluca Brunori (UNIPI), Cynthia Giagnocavo (UAL), Andrea Knierim (UHOH), Daniele Vergamini (UNIPI), Rosa Maria Heredia Hortigüela (UAL), Alessio Ferrari (CNR), Chiara Mannari (CNR), Manlio Bacco (CNR), Trond Selnes (WR), Elisa Ciravegna (WR), Livia Ortolani (UNIPI), Mark Ryan (WR)
0.3	29 March	Document review after consortium check and suggestions	Katrine Soma (WR), Gianluca Brunori (UNIPI), Daniele Vergamini (UNIPI), Livia Ortolani (UNIPI)
0.4	30 March	Typos removed and formatting with EC template	Tiziana Nadalutti (UNIPI)
1.0	30 March	First version approved and released	Katrine Soma (WR), Gianluca Brunori (UNIPI)
2.0	16 September	Second version resubmission	Katrine Soma (WR), Gianluca Brunori (UNIPI)

Contents

Comments by the reviewers and responses by the project 3

Executive summary 11

1. Introduction 16

2. Links between digital technologies and sustainability 17

2.1. Introduction 17

2.2. Sustainable digitalisation 18

2.3. Digital technology provisions 19

2.4. A system thinking approach 21

2.5. Summing up 24

3. A system approach defining costs and benefits 25

3.1. Introduction 25

3.2. LEVEL 1. Business processes and digitalisation 26

3.3. LEVEL 2: Digital ecosystems 32

3.4. LEVEL 3. Socio-ecological systems 38

3.5. Illustrative examples across the three CODECS levels 40

3.6. Summing up 42

4. Costs and benefits of digital technologies related to sustainability 43

4.1. Introduction 43

4.2. System outcomes of costs and benefits 44

4.3. Social benefits and costs 46

4.4. Economic benefits and costs 49

4.5. Environmental benefits and costs 54

4.6. Summing up 56

5. A synthesis - the CODECS Conceptual framework 58

5.1. The CODECS conceptual framework 58

5.2. CODECS – four conceptual scenarios 59

6. Policies for sustainable digitisation 62

6.1. Introduction 62

6.2. Transformative policies 63

6.3. Sustainable digitalisation policies in CODECS 64

6.4. Summing up 66

7. Theory of change for CODECS 66

8. Concluding remarks and future research 71

References 75

Appendix 1. Overview of CODECS living labs 83

Appendix 2. Economic costs and benefits of digitalisation 89

Appendix 3. Overview of definitions 98

List of Tables

Table 1 – Characteristics of a digital ecosystem 33
Table 2 – Examples of how a case can be addressed at different levels 41
Table 3 – Risks related to AI (Source: UN AI advisory body, 2023) 48
Table 4 – Terms used in this document categorised, although nonexclusively, according to possible scales of economic performance (i.e. efficiency, effectiveness, transparency, credibility, accountability/legitimacy and inclusiveness) 53
Table 5 – Policy tools for transformative policies 65

List of Figures

Figure 1 – Components of digital systems (Source: Bacco et al., 2020b) 20
Figure 2 – Simplified system thinking with interactive activities among actors, rules, natural resources and artifacts 22
Figure 3 – Business processes before and after organisation at farm level is digitised 27
Figure 4 – Goal view and structural view of business processes. 27
Figure 5 – User, scaling, and system readiness 30
Figure 6 – The determinants of user readiness (source: McCampbell et al. 2023) 31
Figure 7 – Actors in the AKIS that are directly relevant for agricultural innovation in the food chain (Adopted from SCAR AKIS -2012: 9) 36
Figure 8 – System outputs and system outcomes 44
Figure 9 – Typology of values, adapted from Sandler (2012), Davidson (2013), Turner (2010) and Barbier et al. (2011) 55
Figure 10 – CODECS Conceptual framework 58
Figure 11 – CODECS four scenarios for digitalisation; 1) macro-level social disaggregation, 2) macro-level societal integration, 3) micro-level low social inclusion and 4) micro-level societal integration. 60
Figure 12 – Theory of change for CODECS 70

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Comments by the reviewers and responses by the project

The Table 1 hereinafter provides an overview of the comments made by the reviewers to the 1st version of this document, and the explanation on how the project has dealt with each of them.

Table 1. Overview of the comments made by the reviewers, and the explanation on how we have dealt with each of them.

Comments made by the reviewers of the Deliverable 2.1	Responses made by the authors of the Deliverable 2.1
The deliverable report on the good efforts of the project consortium to tackle a complex, multi and interdisciplinary field of research. The CODECS Conceptual Framework testifies a good effort in synthesising this complexity. However the framework, and the deliverable, can be revised and improved on the following dimensions	NA
Language and writing style:	
The writing style of the first part of the deliverable requires revision for consistency. In few parts the document is called "the study" (p. 3, 8, 14 to name a few, but there might be others)	We interpret your comment to referring to using Deliverable instead of study, and we made this adjustment in a total of 8 cases
Especially in section 1 (introduction) reading the text the impression given is that this is not part of a deliverable of the project (for instance, p. 8 "This research is based on a European research project…", or pag. 9, Box 1)	Like above, we interpret your comment to referring to using Deliverable instead of "this research…", and we made this adjustment in a total of 3 cases. Additionally, in the two cases you refer to we have written: "This Deliverable is part of a European research project called CODECS"
Section 1 is overflooded with questions	In writing the document we thought of a baseline of addressing the relevant questions to this complexity research. In our view, the questions are relevant, not only to the CODECS researchers, but also to the scientific community dealing with similar research. We think you mean that there are too many questions, sometimes overlapping. Therefore, we have removed the questions in the summary and reduced the questions in the concluding remarks and future research section
Pag. 8 lists four research questions (included also in the executive summary): - What are the links between digital technologies and sustainability? - To what extent can a systemic approach assist in defining costs and benefits?	These four questions are all referring to the four main chapters in this Deliverable. They are the main research questions addressed in this Deliverable. We interpret this comment to imply that it is not clear to the reader that there is a link between the research questions and the Chapters, so we have added the following text: "These research questions are addressed in Chapters 2, 3,

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Comments made by the reviewers of the Deliverable 2.1	Responses made by the authors of the Deliverable 2.1
- How are costs and benefits of digital technologies related to sustainability? - What kind of policies can improve the capacity of digital technologies to achieve sustainability?	4 and 6, respectively. Furthermore, Chapter 5 provides a new CODECS Conceptual framework based the reviews conducted in this first part. Chapter 7 provides a Theory of Change analysis to link the findings to other activities that take place in CODECS. Notably, the new CODECS Conceptual framework introduced in this deliverable is addressing costs and benefits also outside the scope of analyses taking place across the activities in CODECS. Finally, concluding remarks and follow-up research questions are provided in Chapter 8”
Section 2 targets a different question (“how do technologies affect the socio-physical world”), summarised in section 2.5	We understand from your comment that the reader will not see any link between the two questions. In order to clarify, we have now written: “In this chapter, in order to better understand the links between digital technologies and sustainability, we investigate how technologies affect the socio-physical world”
Section 3.6 questions "At what level are costs and benefits of digitalisation generated?"	Similarly, to above, we now write in both section 3.1. and 3.6 (now section 3.7): “In order to address the extent to which a system approach can assist in defining costs and benefits, in this chapter we address different costs and benefits generated at different levels”
Finally section 8 formulates further follow-up questions. Questions guided discussion of literature and other evidence is rigorous and relevant, but the use of research questions should be improved through the deliverable, especially providing an answer to those set at the beginning of section 1 (page. 8) and explaining how the former relate to the one explored in section 2	As explained above, we have made the links between the main research questions for chapter 2 and 3, for which we already have explained above. For the last two main research questions we have also made some adjustments to make the links more obvious. This includes the following changes in sections 4.1 and 4.6: “In order to improve our understanding of how costs and benefits of digital technologies are related to sustainability, we investigate in this chapter what the costs and benefits are, and for whom.” As well as the changes made in sections 6.1 and 6.4: “In this chapter we reflect on policies which can improve the capacity of digital technologies to achieve sustainability”
P. 4: the heading says "A systemic approach to assist in defining costs and benefits", the first sentence of the section starts with "A system approach" (system or systemic?)	The right word is system, so we have changed this accordingly throughout the text

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Comments made by the reviewers of the Deliverable 2.1	Responses made by the authors of the Deliverable 2.1
P. 10: the last paragraph of section 2.1 focuses on the term "digital sustainability", while section 2.2 is named "Sustainable digitalisation" and ends formulating a definition of "Sustainable digitalisation". Section 2.5 sums up citing again "digital sustainability". For coherence, these sections should refer to the same concept. P. 59 cites again "digital sustainability" and makes not difference with "sustainable digitalisation". I suggest to clarify because the two concepts do not have the same meaning	According to the work plan we are investigating sustainable digitalization and not digital sustainability. In order to be consequent on this, we have changed all the 26 occurrences of “digital sustainability” to “sustainable digitalisation”
P. 46 and 47: in the bullet list the use of "level(s)" and "step(s)" is confusing.	We have now in all cases referred to the three levels as levels and not as steps
Moreover, there is a typo at row 3, p. 47 (“step 20”, probably "step 2)"	We have changed this accordingly
During the review meeting you also referred to the reference of Vik et al 2021	We added on page 66: Vik et al., (2021) developed a balanced readiness assessment methodology at an organisational level, for which the technology readiness level (TRL) assessment is expanded to include market readiness level, regulatory readiness level, acceptance readiness level and organisational readiness level. While this is an interesting development of the commonly used TRL, in CODECS the coverage would still be too limited because of the strong concentration on an organisation level. In CODECS a sustainability assessment approach is currently being developed for digitalisation, with an expansion to a coverage of social, societal, environmental, economic as well as technological readiness levels (in progress)
Complexity of the framework and clarity of concepts:	
The framework is based on three concepts: Business process, digital ecosystems, socioecological systems. The definition of the three concepts is clear	To improve further the framework, we have now included a new version of the Conceptual framework, in order to make it more clear to the reader
The boundaries, relationships among these concepts are a bit less. It is particularly difficult to understand to what extent the three levels are referred to the technology, to the organisation, or to the environment. see Baker, 2012 - https://link.springer.com/chapter/10.1007/978-1-4419-6108-2_12), especially for the digital ecosystems and the socioecological system	The reference on each level to the technology, to the organisation, or to the environment is now explained more in detail at each level. We have used the reasoning of Baker to explain this at each level (see below)

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Comments made by the reviewers of the Deliverable 2.1	Responses made by the authors of the Deliverable 2.1

1) At business level we write (page 28):

Business process level relationships with technology, organisation and technologies. The relationships between technology, organisation and environmental contexts have been addressed in the literature, including by Baker (2012). In his study, the technology context includes all the technologies that are relevant to a firm, such as those which potentially could be used because they are available in the market. The reasoning of including all these technologies is based on the thinking that there is a limitation of use based on what technologies exist at a certain time. Baker (2012) refers to a second level as the organisational context. At this level both formal and informal factors are influential to adoption of technologies for a firm. The characteristics and resources of the firm are then put central. This includes informal practices of communication and responsibilities, as well as more formalised structures of employees, intra-firm communication processes, firm size, and slack resources. Also, informal linkage agents, may influence attitudes of the firm by referring to positive or negative argumentation of use or no use. At a third level Baker (2012) refers to the environmental context, which to him is specified as industry characteristics and market structure, technology support infra structure and government regulation. Because this is highly confused with the natural environment in a multidisciplinary setting, we replace “the environment” with “the surroundings” in the following.
Comparing the business process level introduced in CODECS with Baker (2012), especially the technology context is similar. Notably, CODECS refers to scaling readiness of the technologies (Damtew *et al.* 2023; Sartas *et al.,* 2020). Also, the firm is the unit of organisation at the business process level, which is highly influenced by technologies (Figures 3 and 4). Note that it is emphasised in CODECS that business processes are highly influenced by factors such as veterinary health checks and advisers, who again are influenced by the customers (Figure 3). As such, some of the external factors in the environmental context as described by Baker (2012) are considered in the business process level.
However, because “the environment” the way it is described by Baker (2012) is seen very limited excluding factors like the digital and natural environment contexts, as well as governance, in CODECS we have defined two more levels. To be able to account for societal, economic and environmental costs and benefits in a broader sense, it is seen critically important to CODECS to deal with the complexities when addressing costs and benefits, rather than to simply referring to market, infrastructure and regulations. Notably, this becomes more visibly when we reach the higher levels of digitalisation level 2: Digital ecosystems and level 3: Socio-ecological systems (SES).
For this deliverable it is emphasised that level 1: Business processes level, involves the understanding of readiness factors. While Baker (2012) refers to a decision-making process, in CODECS we refer to the readiness of a farmer to adopt the technology. Looking at the readiness factors across the interdisciplinary literature, reference to the factors influencing the farmers behaviour include motivation, capabilities and opportunities (McCampbell *et al.* (2023). These are personal characteristics of a farmer, while the scaling readiness refers to the characteristics of the technologies. When the two readiness categories are combined, we refer to this as system readiness (Figure 5)

2) At digital ecosystem level we write (page 32):

At a digital ecosystem level, the technology, organisation, surroundings framework introduced by Baker (2012) becomes less relevant, because organisation does not refer to one firm, but rather the interrelationship with other firms, data, information and actors in interconnected manners, and technologies are not limited to what is in reach by a farmer but address the interlinkages and digital capacities at a large scale. Digital ecosystems are not about decision making of one farmer, but about support to production, storage, communication, and use of digital technologies and data. The surroundings as described by Baker (2012) is still relevant to some extent at this digital ecosystem level, but in CODECS the surroundings also refer to digital, social-economic, organisational, and physical components. Because the natural environment is yet not addressed sufficiently, there is a third level in CODECS, referred to as the socio-ecological level

Funded by the European Union

CODECS has received funding from the European Union’s Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Comments made by the reviewers of the Deliverable 2.1	Responses made by the authors of the Deliverable 2.1
(SES), where also the governance system is addressed in ways that are not too simplistic to understand the costs and benefits from a system thinking approach at a regional scale (Section 3.5). 3) At the socio-ecological level we write (page 38): Looking at the literature, it is informed that the rapid digital expansion offers great new opportunities to society, but it also causes severe threats, for instance, in terms of digital divide and risks for deterioration of the natural environment (Melville, 2010). Assessing the literature on digital divide, we encountered five main areas of relevance; 1) access to the digital, 2) education and digital literacy, 3) socio-economic and socio-cultural conditions, 4) community (e-)networks and 5) governance quality (Ciravegna *et al., in review*). Compared with earlier frameworks linking contexts of technology, organisation and surroundings, this highest level in CODECS would not fit. Instead of using Baker (2012) as a reference, for policy making at national and regional levels, it would be more applicable to deal with societal and natural environments that may risk adverse impacts with new digital developments. Consequences of high inequalities and natural exploitation must from an ethical point of view be dealt with in responsible manners in a market context. As such, policy making can reduce costs and encourage benefits when markets fail to cope with them. Moreover, as stated by the SES, organisations are not limited to firms and institutions and their relationships but include formal and informal norms and values which dominates our minds about what is right and what is wrong, which is the definition of governance (Ostrom, 2011). For instance, the governance context will define whether companies are motivated by employing people in abominable conditions because this is contributing to extended profit margins of the companies, and as a consequence regulation may be needed to safeguarding minimum living conditions with new developments (IPOL, 2019). The environment at the SES level refers to the physical natural environment as well as regulation services provided in the form of nutrient, water and climate cycles, which are critical to human existence and sometimes taken for given with no value attached to them (Soma, 2006). In CODECS, the idea is to address the potential costs and benefits at such a high generic level, following the understanding of costs and benefits at the farm business process level and digital ecosystems level	
All these aspects raise concern on how actionable the framework can be within the project	The Conceptual Framework is foremost meant to address relevant costs and benefits with complexities and system thinking and is not meant to be used for actions within CODECS
In the revision the project consortium shall include two/three illustrator examples to help understand how the different conceptual levels can be used to describe the reality, and how real life phenomena spans across the three layers being distinct but maintaining at the same time contact points	Thanks, we included a new sub-section (page 42): “3.6. Illustrative examples across the three CODECS levels” where we included a table to illustrate the levels to specific cases. See new table 2
Project partners are also advised to consider further literature to inform the framework from a stronger critical and interdisciplinary perspective	The answer to this comment is available hereinafter
Below some suggestions that project partners may consider, and decide if and how to integrate:	
- Information systems literature (e.g. Melville, N. P. 2010, https://www.jstor.org/stable/pdf/20721412.pdf)	We took into account this article in two sections, first on page 59, writing: “Melville (2010) introduced

CODECS has received funding from the European Union’s Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Comments made by the reviewers of the Deliverable 2.1	Responses made by the authors of the Deliverable 2.1
- Melville, N. P. (2010). Information systems innovation for environmental sustainability. MIS Quarterly, 34(1), 1–21 (on digital technologies and environmental sustainability)	a framework linking micro and macro levels by a so-called belief-action-outcome where social structure determines psychic states with influence of individual and social systems behaviours. This is interesting because of the link made between individual and social system behaviours" Also, we included it in the beginning of the environmental impacts section (page 54): "A natural ecosystem involves complex interlinkages of physical components and cycles which are interrelated and creating the needed conditions for biological factors and life (Ackoff 1971). Although the complexities of a natural ecosystem are extremely high, it is possible to link the system thinking itself to information systems because this can mediate or moderate rebound effects by changing data and information availability (Melville, 2010)"
- knowledge gaps around adoption (see this paper by Lowenberg de Boer https://acsess.onlinelibrary.wiley.com/doi/full/10.2134/agronj2018.12.0779)	We included the following text (page 29): "The literature gives clues about causes to sometimes slow adoption of precision agriculture, for instance, Lowenberg-DeBoer and Erickson (2019) refer to biased farmers' perceptions, which often narrow precision farming to only covering variable rate technologies not considering other options, whereas a big gap is identified with the medium and small farmers in the developing world who have no access to it"
- literature on STS and critical social science approaches on sustainable digitalisation (e.g. the work of the following scholars: Kelly Bronson, Emily Duncan, Simon Fielke, Emma Jakku, Callum Eastwood, Anja Bless, Emily Reisman, Patrick Baur, Michael Carolan) - Sociologia Ruralis (e.g. https://onlinelibrary.wiley.com/doi/10.1111/soru.12376	We have included this article on page 23 to reflect on responsibilities by adding: "Responsibility in research on agri-food innovations have also been addressed by Fielke et al. (2021) who argue that perspectives of social sciences from various disciplines can contribute to taking care of the future through collective stewardship of science and innovation by critically reflecting on, among others, dynamics of time and scale for digital solutions, challenges of power dynamics and imagination and practices in shaping futures. Notably, responsible innovation science is also criticised given the way it is linked with technology assessments which is not always embraced because of the risk of reducing the role the technology assessment (Delvenne, 2017)"

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Comments made by the reviewers of the Deliverable 2.1	Responses made by the authors of the Deliverable 2.1
- Agriculture and Human Values (e.g. https://link.springer.com/article/10.1007/s10460-023-10493-9) or https://link.springer.com/article/10.1007/s10460-024-10555-6)	We have included both articles addressing STS. We have added the following texts (page 23): "Linked with the responsible innovation (RI) research is the field of science and technology studies (STS), which is combined with a critical agri-food studies in a special issue edited by Guggang et al., (2023). They look particularly at the roles of powerful actors in policy, industry, technology development and finance and their future vision of food and farming, as well as at instances when agri-food technologies lead to confusion in other food and farming aspects, such as when indoor high-tech trials on plants are returning back to the "wild nature". Tomblin and Mogul (2020) introduce the STS thinker skills which involves a reflexive posture oriented towards humility, openness, criticality and action. Ayris et al., (2024) investigate challenges related with use of automatization in agriculture, including rural unemployment, economic and digital inequalities and unsustainable farming practices, by asking the critical questions: who, why and how are included in engagement processes in ongoing agricultural robotics development process in the UK? They conclude that only certain types of stakeholders are included, with exclusion often being explained by practical barriers such as language barriers. Also, the engagement strategies include meetings, demonstrations, farm visits, etc., but fail to harness different knowledge types. Often the purposes of engagement are limited to technical sophistication and adoption, and are not addressing ethical questions, among others"
- Journal of Responsible Innovation, or Journal of Agricultural and Environmental Ethics	We have included two relevant articles: Delvenne 2017, and Tomblin and Mogul, 2020 (see above)
Minor issues:	
P. 23: the description of the digital ecosystem seems to neglect the social dimension	We have included interrelationships of actors, in addition to data, etc. Also, the social-economic context is included
P. 31: "Three levels of organisation have been identified". The sentence might be confusing, narrowing down everything to the organizational level, neglecting the three levels on top of which the framework is built. I suggest to use the concept of	We are referring to three levels of digitalisation so now we have updated this accordingly

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Comments made by the reviewers of the Deliverable 2.1	Responses made by the authors of the Deliverable 2.1
"organising" to still refer to organisational action- even across organisational boundaries – without limiting the discourse to a single focal entity (a single organisation)	
Baker, J. (2012). The technology–organization–environment framework. Information Systems Theory: Explaining and Predicting Our Digital Society, Vol. 1, 231-245	The answer to this comment is available above

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Executive summary

Digitalisation may bring significant benefits in terms of efficiency in farm production systems, water use and reduction of pesticides. However, digitalisation may bring costs to our societies, in terms of social exclusion and a more unequal society, among others.

Introduction

The CODECS project is designed to contribute to sustainable digitalisation, including economic, environmental and social sustainability, thus covering advantages and disadvantages. The main focus of CODECS is on digitalisation, referring to the process of socio-economic-ecological-technical change related to digitisation. **Digitisation is here understood as the increased use of digital technologies in business and management.** The links between economic, environmental and social value-dimensions in transition processes are complex given possible feedback loops and unforeseen influences. The urgency of making use of system thinking is increasing lately, due to interlinkages leading to systemic responses with unintended hindrances of achieving sustainable solutions. System thinking offers the idea to investigate influences across and between factors, and not simply looking at linear evaluation approaches. Given the little knowledge available about the actual reduction of negative environmental and climate effects of digitalisation, the main aim of this deliverable is to develop a conceptual framework. Such a conceptual framework contributes by providing a set of rules for organising and understanding a particular problem, providing the basis for theoretical development and for empirical research related to it. It selects the key concepts that will be used to describe and interpret the problem and establishes relationships between concepts. Moreover, a conceptual framework sets the basic assumptions that will drive theoretical and empirical research and defines the boundaries of the research.

This deliverable is not outlining the methodological approach in CODECS, but rather provide the CODECS Conceptual framework, designed to improve understanding of the complexities of the transition towards sustainable digitalisation in Europe. This CODECS deliverable has defined the following main research questions:

- What are the links between digital technologies and sustainability?
- To what extent can a system approach assist in defining costs and benefits?
- How are costs and benefits of digital technologies related to sustainability?
- What kind of policies can improve the capacity of digital technologies to achieve sustainability?

These research questions are addressed in Chapters 2, 3, 4 and 6, respectively. Moreover, Chapter 5 provides a new CODECS Conceptual Framework based the reviews conducted in this first part, and Chapter 7 provides a Theory of Change analysis to link the findings to other activities that take place in CODECS. Notably, the new CODECS Conceptual Framework presented in this deliverable is addressing costs and benefits also outside the scope of analyses taking place across the activities in CODECS.

Links between digital technologies and sustainability

The increasing use of technologies affects the socio-physical world. The term ‘digital technology’ covers a huge number of devices, infrastructures, protocols, applications, with many possible combinations. Each of these components is linked to specific actors, developers, dealers, users, and intermediaries. These components are often linked with each other by, on the one hand, devices attached to their software, and on the other hand, devices connected to other devices. Technologies, or assemblages of technologies, are adopted by farmers in different commercial forms, for example, as goods or as services. Because it is not possible to assume that the development of digital technologies is independent from the needs of different farmers and from different agricultural paradigms, the question is whether there is room to give technology development a direction. Because “there is little knowledge about the actual reduction of negative environmental and climate effects due to their application”, this is not clear. Given that in CODECS sustainable digitalisation is highly related to main risks associated to digitalisation, such as the generation of inequalities, the following definition has been adopted: **Sustainable digitalisation is a process of social transformation by which digital technologies are embodied into socio-economic life to promote intra-generational, inter-generational, inter-species wellbeing, reduce inequalities, and improve the health of ecosystems.**

CODECS has received funding from the European Union’s Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

A system approach to assist in defining costs and benefits

A system approach does not only investigate collected components within a context, but also look at how they are interacting. A socio-cyber-physical system, for instance, refers to interactions between the three components. Whereas 'social' refers to social actors, groups, communities and institutions, 'cyber' refers to original digital constructs such as software, big data, cloud computing and IoT, as well as digital reproduction of the physical sphere. "Physical" refers to the natural resources as well as the artificial. When digital technologies are applied to human activities, they become part of broader socio-technical systems. To be more precise, referring to socio-cyber-physical systems, the elements can belong to the social, physical, and to the digital sphere. The relevance of using the socio-cyber-physical concept is that it helps to predict any change that one sphere will generate into others. Likewise, rules and resources that characterise one sphere can affect the others, in so-called loops.

Considering digital technologies as components of broader socio-technical systems implies a deeper understanding of the systemic nature of costs and benefits. Digital technologies disconnect and reconnect elements of the system; new rules and new routines are created; new resources are used, and old resources are abandoned. All these processes need time. A system analysis of costs and benefits, therefore, implies the analysis of; 1) processes of change, 2) intermediate outputs generated along the process, and 3) the distribution of the effects among the system components.

The system approach implies the understanding of reality as structured in different levels of complexity. Complexity implies that relationships between components are not linear, as each output can be generated by multiple causes; effects can be both direct, indirect, and retarded; interaction generates feedback and synergies. Interaction of system components generates emergent properties, generated and enacted through interaction between components and unobservable when analysing individual components.

In CODECS, three levels of digitalisation have been identified for the analyses: 1) Business processes, 2) Digital ecosystems, and 3) Socio-ecological systems.

First, at a basic level, **business processes** refer to farm related processes as they are, and farm related process as they become after digitisation, i.e. after the introduction of the digital technology. The business development on the farm depends on processes of readiness, which depend on the capabilities, motivations and opportunities at farm level. User/farmer readiness can be scaled to involve multiple farms, and this can result in readiness at larger scale, i.e., system readiness.

Second, at a higher level, **CODECS define digital ecosystems as an organised set of digital, social-economic, organisational, and physical components that support the production, storage, communication, and use of digital technologies and data**. A digital ecosystem provides the resources necessary to support the digitalisation of processes at farm level, including connectivity infrastructures, organisational resources, human resources, knowledge, data and platforms. If it does so, we may consider it a "conducive" digital ecosystem. The analysis of digital ecosystem will proceed in three phases. The first phase involves the preparation and the review and use of available information. The second phase entails interacting with living labs and stakeholders to co-create and validate the digital ecosystem characterisation, including identifying resources, capabilities, collaborations, and innovations, the definition and validation of indicators, and the development of process diagrams for information exchange and comparison due to the adoption of digital technologies.

Third, at the highest level of analyses of costs and benefits of digital technologies, interactions between human activity-based processes and natural resources investigated at farm level are brought up to higher level. In this level, the Ostrom framework of **socio-ecological systems (SES)** is adopted. The original Ostrom´s SES approach assesses the sustainability of natural resources through the analyses of drivers that generate pressures on them. On this regard, the framework states that human activities, i.e., the actor´s subsystem, use resource units in their processes. Moreover, in SES resource **units,** i.e., assets used by actors in agriculture and rural economies, are enclosed by **resource systems, i.e.,** trees in the forest, fishes in the ocean environment, sheep in the grasing systems Therefore, resource systems are made up of interlinked resource units, including social, economic, technological, and environmental assets.

The **actors,** i.e., individual and collective, carry out **activities** involved inhabit particular contexts, with their own interests, ambitions, capabilities, access to resources, knowledge levels, and beliefs. In turn, activities are regulated by rules and norms generated by governance systems. **Governance systems** can be defined as the rules that

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

establish how decisions are taken. Governance systems are structured through constitutional rules, contractual arrangements, accountability systems, strategic exercises, traditions and routines. As governance systems define the distribution of costs and benefits of human processes, they are the dynamic outcomes of power relations between the actors that compose them, and it is not rare that rules generated by governance systems are not coherent with each other. The analysis of the impact of the governance systems on human activities is the key to the sustainability assessment of resource management, and consequently to the introduction of digital technologies.

Costs and benefits of digital technologies related to sustainability

Following a **socio-technical system approach**, the costs and the benefits can be addressed according to some eight main entities, including timeframe, context, system needs, system entities (who?), system relationships (how?), system activities (what?), system expectations, and impacts.

From a **social perspective**, operating at the general (society) level, CODECS addresses benefits and costs by first illustrating the difficulty of defining them. While it is possible to specify for instance consumers, employment or health care as social dimensions for the analyses, social benefits and costs can also be defined across individuals, access, rights, social capital, and control. Moreover, social impacts can be about farmer/user readiness are linked with internal drivers, like capabilities, opportunities and motivation, or social divide. In the arena to digitalisation, categories of risks can be specified for individual, group, societal, economy, ecosystem, and value-norms related risks. Following the farmer/user perspective, a specific methodology that is merging various disciplinary fields (social sciences, management sciences, ergonomy, etc) has been elaborated in CODECS in order to inform the farmers about the ways a digital technology has changed the practice and the life of other farmers.

From an **economic perspective**, the costs and benefits can be addressed in terms of productivity, services, and livelihood, or be associated with outcomes at organisational, value-chain or market areas. Following a business process perspective, the costs can be analysed according to productivity, quality of products, revenue, input costs, variable costs, crop wastage and energy use, but can also take into system costs to cover operational costs, transaction costs, switching costs, etc.

Digitalisation at farm level takes time, as it implies a continuous adaptation and reconfiguration of the social, physical, and digital components of the business process. CODECS identifies three stages of digitalisation at farm level, each of them characterised by several types of costs: a) setup; b) transition; c) full operation. The distinction is relevant as setup and transition requires investments for which the return on investment should be assessed.

The **environmental benefits and costs** are also complicated because the environment is a system itself where all components are interdependent and interrelated through climate cycles, water cycles and nutrition cycles, among others, which form the baseline for our existence, but highly falling out of our valuation systems. At a global level, we can follow the typology of environmental values, categorised as benefits to nature and benefits to humans, non-use and use values, warm glow and existence values, option values and actual values, indirect and direct values, consumptive and non-consumptive values. As such, these dimensions are non-commensurable, and show that some are not directly observed to relate with human wellbeing. Hence, thinking of value-systems as intra-psychic constellations of norms and perceptions that guide human judgement and action, only some of the environmental values are considered. But, before considering values, more straightforward methods allow biophysical assessments of the potential environmental impacts.

The CODECS Conceptual framework

The CODECS Conceptual framework operates in an ever-changing contextual situation, impacted by **external drivers**, such as social, technical, environmental and political drivers, as well as **internal drivers**, such as capacities, motivations and opportunities. Explanatory to the transition of the system, the external and internal drivers influence the **contextual factors** of entities, relationships and activities in a particular context.

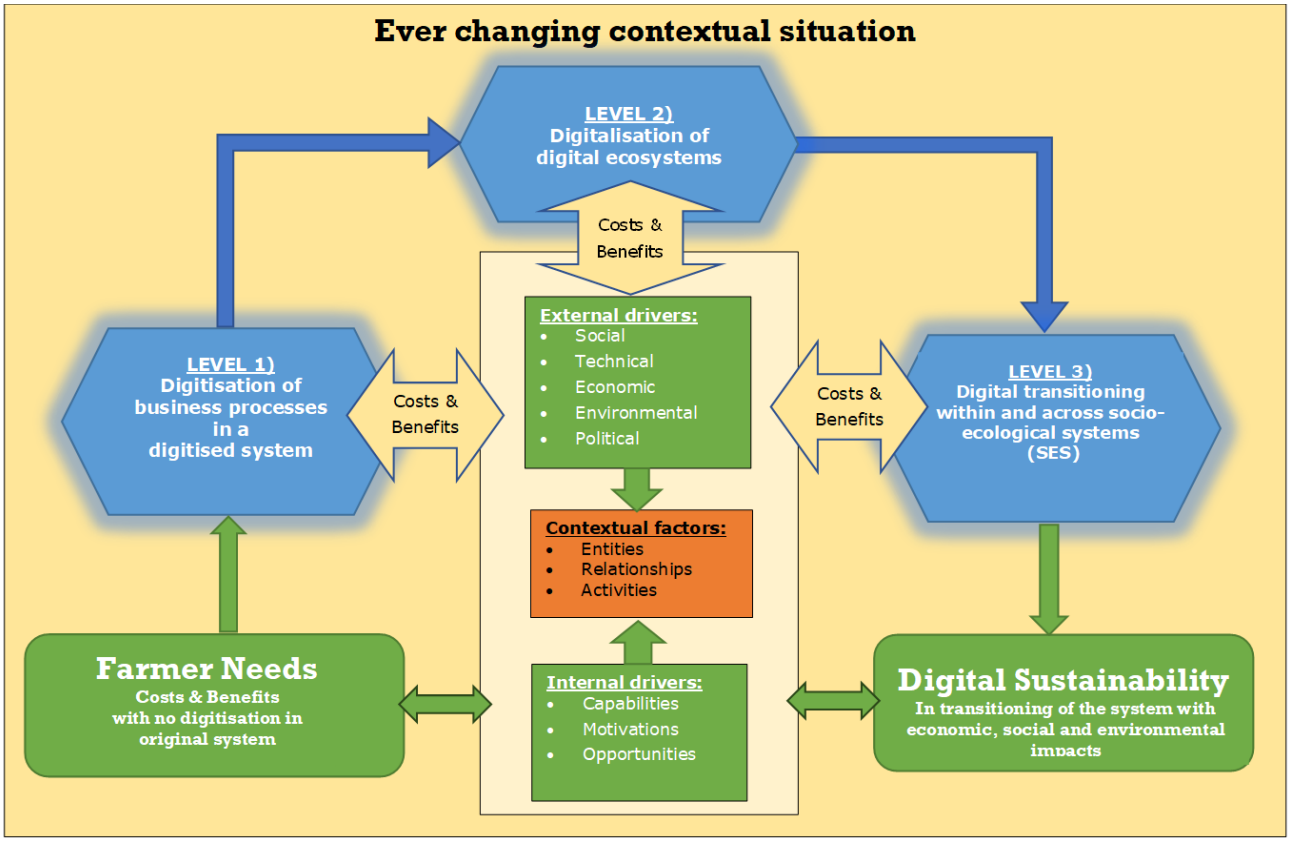
CODECS is designed to begin with farmer's needs, for so to follow the transitioning towards different levels of advancements. In CODECS we specify the transitioning from a baseline level referred to as 'socio-physical system', where no digitalisation yet has taken place. The advancement to a first level to reach at a digitised socio—physical system, is caused by digitisation of business processes, triggered by among sensing-actuation and user readiness factors. With digitalisation, the advancement to a second level referred to as socio-cyber-physical system takes place. With digitalisation, impact reach covers digital ecosystems, Agricultural Knowledge and Innovation System

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

(AKIS), and system readiness factors. The transitioning from a socio-cyber-physical system to a transitioned socio-cyber-physical system, requires transitioning with even larger reach. In order to explain this third level of transitioning, the socio-ecological system approach is helpful, because of reference made to interactions and outcomes among and within natural and digital ecosystem, governance, resource units and actor interactions. Throughout the different system levels impacted in different reach of digitalisation, the context is ever changing. This implies that there is no such as one estimate of costs and benefits in a particular context, because the values will change over time, in parallel with the advancement of the transition process. In short:

1. Moving from a basic socio-physical system level where the farmer needs is put central, to a digitised socio-physical level, main causes to change are occurring at the business process level. Notably, also the contextual external and internal drivers will interact, thus resulting in different costs and benefits across different contexts.
2. Moving from a digitised socio-physical system to a socio-cyber-physical system is made possible through digitalisation, which have larger coverage than the farm level alone. In digitalisation, the digital ecosystems and the AKIS influence system readiness to digitalise. Also, this change is impacted by contextual external and internal factors, which interact with the process of digitalisation. The environmental, economic and social costs and benefits will vary from the previous levels.
3. Moving from a socio-cyber-physical system to a transitioned socio-cyber-physical system, such change is triggered by a wide reach of influence by the digitalisation. This can be explained by the SES, for which interaction and outcomes appear within and across ecosystems, natural resources, governance and actor interactions.



At each of the three levels, the costs and benefits will differ in scope and character. While our starting point is the farmer needs, the transition refers to a societal context broadly speaking. Whereas level 1) begins with the farmer, level 2) includes the associated network to the farmers, and level 3) covers the whole Socio-Ecological System

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

(SES) in a broader scope of the analyses involving interactions within and among natural and digital ecosystems, governance systems, the resource units, the resource systems and the actors.

Hence, the design of such socio-cyber physical system comprises some three core critical components referred to as: design, access and complexity. **Design** focuses on the challenges that the technology is supposed to deal with, as well as user needs and potential risks. A decision on a particular technology can have positive and negative impacts on sustainability issues, such as inclusion, exclusion of different societal groups in a socio-ecological system and can deal with the regulation ecosystem services, in particular. **Access** refers to infrastructure, human capital and financial resources, as well as human and system readiness levels, which can affect access conditions to the new technologies in different manners. These factors link us to the main causes of digital divide. **Complexity** describes the systemic conditions for adoption and scaling with digital technologies. This refers to interconnectedness in a well-functioning socio-cyber-technical network, with interoperability, which provide the opportunities for exchange, pool and integrate data between actors and devises. Complexities in a transitioned socio-cyber-technical system link with the natural and digital ecosystem components, as well as with the governance system, with implications for long term sustainability.

In CODECS one of the core intentions is to facilitate digitalisation of farms, while minimising any corresponding risks, to increase farm productivity and efficiency, improve quality of work and reduce pressures on natural resources. From this perspective, CODECS identifies and accesses a full range of costs and benefits stemming from the adoption of digital technologies in farming. These costs and benefits can be environmental, economic, and social and are viewed within CODECS as the decrease or increase of actors' capabilities to utilise resources in short and long term to reach their objectives (revenue, food production, etc.). In CODECS, the environmental costs and benefits of digitalised production processes are analysed. Economic costs and benefits are analysed through the estimation of technical and economic indicators as well as of basic financial results at the farm – and system – levels. When it is impossible or too complex to make quantitative assessments, especially when it comes to ecosystem services, social benefits and costs, qualitative or mixed indicator-based farm level assessments will be carried out.

CODECS makes a significant contribution to establish a basis for the development, implementation and evaluation of sustainability- and data-related policies at regional, national and EU level and reaching related objectives, including Green Deal ambitions, the new CAP, and the 2030 Digital Compass. For the socio-cyber physical system level in the CODECS Conceptual framework, the following activities can have positive impacts. First, the problem definition phase can benefit from the research activities that took place across the 20 living labs at a business process level, and second, the knowledge generated throughout the CODECS can eventually benefit the agenda setting for future policy making at a digital ecosystem level, because the knowledge of risks of costs and benefits have been estimated. Third, the outcomes of the analyses across the different work packages and throughout the living labs will provide proven insights scientifically, which will support future policy implementation in complex contexts to ensure policy implementation will trigger more than hamper the transitioning towards the SDGs by enhancing social, environmental and economic benefits at all levels, and reducing costs.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

1. Introduction

Following the Green Revolution in the 1950s, it was common understanding that the sustainability of the agricultural performance had gotten limited attention, because of limitations of, among others, available agricultural inputs, labour and energy (Patel, 2013; Pretty and Bharucha, 2014). With digitalisation of the agricultural sector, new opportunities emerge that can cope with some of these limitations, among others, by rapid development of communication networks and the availability of a wide range of new remote, proximal, and contact sensors (Bacco *et al.,* 2019). Data gathering, processing and analyses provide data that assist in determining the state of the agricultural context including soil, crop, and climate. Further advancements through Internet of Things, sensors, robotics, artificial intelligence, big data, cloud computing, etc., currently leads the transition towards a fourth revolution, which possibly provides fair, resilient and sustainable agricultural growth that can deal with needs of the future global population (Javaid *et al.,* 2022; Bradu *et al.,* 2023; Abbate *et al.,* 2023). However, this positive assumption of a linear link between digitalisation of the European agricultural sector leading to social, economic and environmental sustainability is challenged. On the one hand, a knowledge "gap" exists between the portfolio of digital technologies offered at the market and the actual uptake and use by farmers in the EU. On the other hand, while the potential of digital technologies to better tailor agricultural production is widely acknowledged, there is little knowledge about the actual reduction of negative environmental and climate effects due to their application.

In this deliverable, although it is acknowledged that digitalisation in agriculture can generate benefits as well as costs, and can contribute to sustainability, the main concerns are the potential risks that; 1) benefits will not necessarily overcome costs, and 2) costs and benefits will not necessarily be distributed equally. The possibilities to have sustainable digitalisation depend on the pathways of digitalisation, which is a socio-technical transformation (Mäkitie *et al.,* 2023; Jabłoński and Jabłoński, 2022). Communities face challenges in dealing with all the levers they are endowed with (values, ideas, knowledge, regulation, financial resources, entrepreneurship energies) at local, national and EU levels instructed for technology development, societal embodiment and sustainable direction. In agriculture this challenge is related to the consideration that agriculture is one of the most important sources of pressure on natural resources, and that the food system is characterised by strong inequalities. One of the causes of the malfunctioning of food systems in the world is the application of an agricultural paradigm, the Green Revolution, that has prioritised economic productivity and disregarded environmental and social impacts (Brown, 1970; Horlings and Marsden, 2011). The Green Revolution has favoured specialisation and scale enlargement, making it fit with the evolution of the food system into long distance supply chains operated by big players (Giller *et al.,* 2021).

Hence, while digitalisation can be a key driver of transformation, this depends on the agricultural and economic paradigm to which it applies, which can lead to digitalisation resulting in very different impacts. The challenge of a sustainable digitalisation, as a consequence, is to design digitalisation scenarios consistent with sustainability goals, as for example made explicit during the United Nations Food System Summit 2021. Given the little knowledge available about the actual reduction of negative environmental and climate effects of digitalisation, **the main aim of this deliverable is to develop a conceptual framework.** Such a conceptual framework contributes by providing a set of rules for organising and understanding a particular problem, providing the basis for theoretical development and for empirical research related to it. It selects the key concepts that will be used to describe and interpret the problem and establishes relationships between concepts. Moreover, a conceptual framework sets the basic assumptions that will drive theoretical and empirical research and defines the boundaries of the research. For the specific purpose of this deliverable, the following research questions are at the centre the framework development:

- What are the links between digital technologies and sustainability?
- To what extent can a system approach assist in defining costs and benefits?
- How are costs and benefits of digital technologies related to sustainability?
- What kind of policies can improve the capacity of digital technologies to achieve sustainability?

These research questions are addressed in Chapters 2, 3, 4 and 6, respectively. Furthermore, Chapter 5 provides a new CODECS Conceptual framework based the reviews conducted in this first part. Chapter 7 provides a Theory of Change analysis to link the findings to other activities that take place in CODECS. Notably, the new CODECS

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Conceptual framework introduced in this deliverable is addressing costs and benefits also outside the scope of analyses taking place across the activities in CODECS. Finally, concluding remarks and follow-up research questions are provided in Chapter 8.

In exploring the links between digital technologies and sustainability, in this deliverable the basic assumption is that costs, benefits, sustainability gains and losses must be identified to be able to analyse and produce knowledge to the benefit of EU policies. This deliverable is part of a European research project called CODECS (See Box 1). In a multi-actor project like CODECS, the materials necessary to build a conceptual framework come from different disciplines, different theories, and empirical insights from a variety of real contexts. The co-development of a conceptual framework within a multi-actor consortium contributes to achieve a common understanding of problems, fostering mutual understanding and the development of a common language, paving the ground for a common understanding of the implications of alternative solutions to the problem.

Box 1. CODECS – This deliverable is part of a Horizon Europe project: https://www.horizoncodecs.eu/

CODECS has the ambition to strengthen the digitalisation of farming to arrive at increased productivity, improved efficiency and quality of work, reduced pressure on natural resources, and promote market integration. Moreover, CODECS strives to enhance farmers' access to knowledge, foster peer-to-peer learning, support innovation networks, improve rural-urban and producer-consumer links, and reduce bureaucratic burdens. At the same time CODECS focuses on avoiding or reducing risks for disadvantages that could follow the process of digitisation. These include reduced opportunities of economic, social, and environmental prosperity for specific vulnerable individuals, communities and regions across the EU. However, the real benefits and costs are highly unclear from a societal point of view. Therefore, CODECS also strives to improve the collective capacity to understand, assess and foresee the full range of benefits and costs of farm digitalisation, and to build digital ecosystems that maximise the net benefits of digitalisation.

CODECS develops a vision of "sustainable digitalisation", supported by concepts, methods, tools and evidence. Sustainable digitalisation describes the process of transformation that affects the physical, the social, the technical spheres of multilevel human activities, as well as contributions to the socio-economic transition needed for future agri-food system to respond to upcoming economic, social, and ecological challenges. This socio-economic-ecological technical transformation contributes to the realization of SDGs. To support these broader processes of transition, CODECS takes up the challenge of improving the capabilities needed to meet the demands of sustainable digitalisation. For this we engage in a co-creation of a common vision, a conceptual framework, a methodological framework and outreach strategies to the 20 Living Labs in CODECS, which represent a large variety of the agricultural sector in Europe.

CODECS differs from many other European Horizon project by its focus on co-developed by the entire consortium, following a transdisciplinary approach to theory building towards a shared vision of sustainable digitalisation. Based on the multiple contributions, insights and findings developed across research disciplines, a common research approach will dynamically evolve as the project unfolds. After delivery to the European Commission, the common research approach will be validated and refined in online and face-to-face workshops by means of the participatory theory building among researchers and Living Lab (LL) activities. Eventually, the final documentation of the common research approach will be provided in the form of a policy brief (M40).

2. Links between digital technologies and sustainability

2.1. Introduction

In this chapter, in order to better understand the links between digital technologies and sustainability, we investigate how technologies affect the socio-physical world. Notably, the term 'digital technology' covers a huge number of devices, infrastructures, protocols, applications, with many possible combinations. Each of these components is linked to specific actors, developers, dealers, users, and intermediaries. These components are often also linked with each other by; on the one hand, devices attached to their software, and on the other hand, devices connected to other devices. Technologies, or assemblages of technologies, are adopted by farmers in different commercial forms, for example, as goods or as services. Because it is not possible to assume that the development of digital

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

technologies is independent from the needs of different farmers and from different agricultural paradigms, the question is whether there is room to give technology development a direction.

First in this chapter we introduce the term sustainable digitalisation, which is the overall goal of the activities in CODECS. Based on a short review of relevant literature, a specific definition of sustainable digitalisation as it would fit in CODECS is formulated. Second, digital technology provision is explored by referring to a series of interrelated concepts, including digitisation, digitalisation, sensing, actuation, computing and intelligence. This is followed by a general introduction of system thinking, by a simplified illustration of core activities among actors, artifacts, natural resources and rules, influenced and by drivers and outcomes. Moreover, we introduce the terms socio-technical systems and socio-cyber-physical system, which create important building stones in the CODECS Conceptual framework introduced in Chapter 5.

2.2. Sustainable digitalisation

The literature on sustainability and sustainable development is rich and can be tracked back to the well-known "Our common future" (Brundtland, 1986), referring to the three pillars of environmental, economic and social sustainability, and defining sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs, with emphasis on limitations imposed by the state of technology, social organisation and the environment's ability to meet present and future needs". Further, the United Nations General Assembly (UN, 2015) contributed significantly to the sustainability agenda by defining the 17 Sustainable Development Goals (SDGs), including sustainable cities and communities (SDG11), decent work and economic growth (SDG8), reduced inequalities (SDG10), as well as climate action (SDG13), life below water (SDG14), and life above water (SDG15). For the definition of sustainable digitalisation provided by UNEP, which is often used as a benchmark, it specifies that; "sustainable digitalisation is the compass that guides us toward a future where technology empowers society while minimising its environmental footprint". In this definition, 'empowering society' addresses social impacts, and 'environmental footprint' addresses the ecological impact of digital technologies.

However, when linking sustainability to digitalisation, the scientific literature is rather scarce, although increasingly sustainable digitalisation appears a relevant term in the literature the latest years. For instance, Sacco *et al.* (2021) analysed the relationship between digitalisation and sustainability, intending to provide an integrative and sustainable perspective and life cycle view. In their analyses they unravel that, whereas earlier the focus was more on one sustainability dimension, latterly all three main dimensions are in integrative manners addressed simultaneously in the same studies. Comparing the three dimensions, they also find that the social sustainability impacts, both negative and positive, are more frequently addressed than the economic and environmental ones only. Given the substantial number of negative impacts that have been addressed, it is not possible to assume positive sustainability impacts of digitalisation. As such, this reasoning of the digitisation – sustainability links is based on the basic definition of sustainability.

An alternative entrepreneur-based approach to analyse industrial digitalisation – sustainability links are provided by Niehoff (2022), by referring to "Industry 4.0", to create interconnected, adaptive, and efficient cyber-physical systems by combining advanced technologies, data connectivity, and intelligence. Basing their analyses of a total of 30 sustainability reports filled in by the industry, asking some critical questions to unravel whether digitalisation most likely will accelerate unsustainable growth, or support a more sustainable economy, they concluded that a predominant weak or business-centred sustainability approach appears, which could lead to the acceleration of unsustainable growth. The main factors leading to this conclusion are the overall focus on customers' demands, the economic perspective of faster and more efficiency, and the understanding of digitisation as support to 'business as usual'.

Yet another perspective is held to address the digitalisation – sustainability link by Mondejar et al (2021). They explore how digitalisation can assist in attaining the SDGs in a total of four predefined sectors: 1) the food-water-energy nexus, 2) the industry, 3) the citizens health and well-being, and 4) the climate change and biodiversity protection. They show nicely how 14 of the 17 SDGs fit into the analyses. They conclude that digital technologies are up-scaling with proper agricultural land and resources management and strengthened through productivity,

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

services and livelihood security worldwide. While this study points to overall positive impacts of digitalisation on sustainability, they also mention that special attention should be paid to equal data access, digital poverty, increased inequality and cyber security.

In a study carried out by Rolandi *et al.* (2021), they refer to the challenge of deriving an exhaustive analysis of impacts digital technologies have specifically in rural areas, with the aim to provide an extensive framework for such analyses. They base the method on a so-called "digital tool", where they define the main domains of sustainability, adding the governance domain to the commonly used pillars of economic, environmental and social domains. Following a Theory of Change (ToC) logic, they specify impact areas and outcomes to each domain. Based on a literature review, they specify the following impact areas:

- Economic areas of operation: organisation, value-chain and market
- Environmental areas of operation: animal well-being, ecosystem services, natural resources and risk management
- Governance areas of operation: operationality, equity
- Social areas of operation: individual, access, rights, social capital, control

The outcomes have a long list of options, for instance, for the economic domain, productivity, marketing, and transparency are examples, while for the environmental domain, outcomes like water, soil, energy have been specified. The outcome options identified for the social domain are the most in numbers, and include for instance, power, equity and skills, whereas the governance domain has the smallest number of outcomes specified, including participation, cooperation and administrative burden. While they acknowledge a series of positive impacts of digitalisation on sustainability, they also refer to some risks including that improvements will only benefit a few farmers, reduction in human control, and lack of knowledge of ethical issues (see also van der Burg *et al.,* 2019).

The different insights provide different perspectives to how to best analyse the links between digitalisation and sustainability. One of the challenges of digitalisation is that the level of uptake of these technologies, despite the opportunities that digital technologies offer, is limited, which has been argued to provide a barrier to a faster achievement of sustainability goals. The question is whether more intense uptake of digital technologies necessarily brings the society to a more sustainable agriculture? Given that "there is little knowledge about the actual reduction of negative environmental and climate effects due to their application", this is not clear. Given that in CODECS sustainable digitalisation is highly related to main risks associated to digitalisation, referring to the generation of inequalities, the following definition has been adopted:

Sustainable digitalisation is a process of social transformation by which digital technologies are embodied into socio-economic life to promote intra-generational, inter-generational, inter-species wellbeing, reduce inequalities, and improve the health of ecosystems.

2.3. Digital technology provisions

Digital technologies can provide a representation of the physical world in terms of numbers: the process of representing the physical world through numbers is called **digitisation** (Metta *et al.,* 2022). **Digitisation has more precisely been defined as the technical conversion of analogue information into digital form** (Autio, 2017). Because the computers provided the opportunities to automated processes, thus providing the opportunities for reducing the manual activities substantially, digitisation led to the third industrial revolution (Greenwood, 1997), which was followed by the fourth industrial revolution, referred to as the digitalisation (Schwab, 2017). With digitalisation, people's routines get redefined according to digital transformation into new economic, environmental, social and governance domains (Rolandi *et al.,* 2021). Whereas digitisation opens the way to digital transformation by reorganising physical, social, and digital relationships, the process of digital transformation is referred to as **digitalisation**.

With regard to digitisation, one of the latest achievements of digital technologies is to extract the signals of the physical world (temperature, humidity, movement, etc.) without human mediation and to translate them into numbers.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

This process is called **sensing** (Figure 1). Sensing refers to the use of sensors in precision agriculture and provides the opportunities to gain large amounts of relatively inexpensive information on the spatial and temporal variation in crops, soil, weeds, diseases, etc (Mulla *et al.,* 2021). A wide range of sensors exist that can be used for different purposes, including satellite remote sensing for precision agriculture, sensing crop geometry and structure, soil sensing, sensing with wireless sensor networks, sensing for health, vigour and disease detection in crops, sensing in precision horticulture, sensing for weed detection, among others.

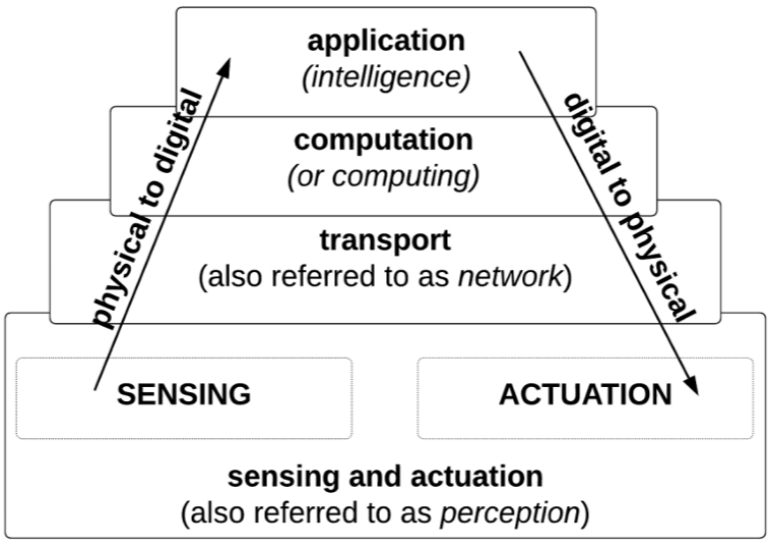


Figure 1 – Components of digital systems (Source: Bacco et al., 2020b)

Digital technologies can also change the physical world by turning numbers into instructions for physical devices; this is called **actuation**. The actuation, i.e. the action and decision making, executes the decisions made according to the sensing followed by an intelligence process (Emmi *et al.* 2014). Such Internet of Things (IoT) based application collects data by means of sensing, the data goes through a data network and computation, and is thus communicated from one device to another, before it is offered to a farm application (from physical to digital). Such applications provide different types of services, which again generate data (from physical to digital) (Bacco *et al.,* 2020a; Bacco *et al.,* 2020b). Once the data is digitised, it can be replicated and stored (**computing**), and further it can be elaborated according to a process (i.e. data→machine→ data). Elaboration allows the transformation of data into information, which is data endowed with a meaning referred to as a process called **intelligence**. The term 'intelligence' has no standard definition but can be referred to as "ability for reasoning, problem-solving, and learning" with more intelligence. It becomes possible for the technology to learn fast and make use of experience (Gottfredson, 1997). Notably, in a complex world, humans are not always rational (Kahneman, 2011). Instead, machines can have the abilities to tackle loads of information and sort out complexities that humans have no chance to deal with. Artificial Intelligence (AI) refers to when machines can make use of the data and carry out tasks similar a human being, which can be defined as; "computer's ability to recognise patterns and take actions based on available data and statistical models". However, there are multiple classifications of AI which is outside the scope of this deliverable (Hassani *et al.,* 2020). At a more basic level, digital intelligence processes allow performances of tasks such as monitoring, classification, prediction and content generation.

Box 2. CODECS – Technology applications at different TRLs across Living labs (Appendix 1, Table A11)

A total of eight of the 20 use cases have reported to have a technology readiness level (TRL) of 7, which is relatively high, all aiming at enhancing the sustainability of the living labs. In Latvia for the beef production, they employ the SSA GEO map environment to an emerging food product brand "Grassland Product Label" that focuses on products from semi-natural grasslands characterised by high biodiversity, and in Serbia they make use of IoT sensor node in greenhouses for production of vegetables, to reduce use of water and increase agricultural effectiveness. In France they apply tank weight scales, combined with weather station etc., to investigate sheep, and a so-called Occitanum Open Lab Viticulture for fertilisation modulation decision support

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

system according to vigor maps to reduce inputs and adapt to climate change by mobilising a pilot territory. In Ireland they have established a market for local product by a digital route to market for local food producers to shorten long supply chains and address the climate and ecological emergency and support accessing markets, whereas in Belgium, they use ultra-high resolution RGB on drones and AI for detection of weeds, diseases, and pests in potato crops. The wine makers in Slovenia use IoT in vineyards and honey production, to establish a demo IoT beehive environment to enable research on new solutions, for example how to find a queen in the beehive and monitor her behaviour, and in Slovakia they use new sensors to detect mobile application for determining the irrigation dose for agronomists.

Ranging from TRL3 to TRL6, a total of eight living labs have reported a lower level of readiness of the technologies they use. In Poland they upgrade IT-PLM software for increasing the performance & scale of a virtual marketplace with buyers & sellers (farmers) for local markets for locally produced food, while in Latvia/Estonia they use drones will be used to test their effectiveness for managing different grasslands in Latvia. In Scotland, digital platforms for training and collaboration with small farm producers is used to enable them to adopt relevant digital tools to promote sustainable and transformative applications in their farm practices, and in Almeria, related with greenhouse production, integration of data generated by the IoT ecosystem in a centralised platform facilitates optimised control and management for the generation, storage, reuse and use of resources to control the climate, enrichment, and fertigation. In Macedonia, a remote Agricultural Monitoring and Advisory System, to optimise agricultural inputs and processes, increase effectiveness in decision processes is developed, and in Italy a Farm Management Information System (FMIS) is used to monitor sheep health, feeding information, quantity, and quality of milk production. Whereas a new sensor-based orchard management system for crop protection, remote control of the irrigation system, frost and pollination monitoring and an end-user application for the farmer is employed in the Czech Republic, technologies for pig farming at different stages to improve their welfare: monitor feeding and barn environment, following the behaviours / postures of the animals, is used in France.

Yet, some four more living labs have reported advanced TRL's of 8 and 9. This includes the living lab in Italy, using sensors in orchard and Decision Support System (DSS) to manage the organic table grape production, and se of sensors at field level (soil, environment and crop) interconnected and in communication with a DSS, and the development of vocational education related formats to support knowledge building on digital technologies for prospective farmers and agricultural educators in Germany. In Greece they use a spraying drone, which refers to any UAV, operated manually or automatically, that is capable of applying agrochemicals at a desired rate close to the canopy (commonly <5m), and in Hungary they innovative soil scanner system in soil nutrient management advisory (hardware, software, web-based platform, mobile application) for a more sustainable farming. These two last living labs have a TRL of 9 and are thus reported as the highest technological readiness levels.

2.4. A system thinking approach

The variety of tasks that digital technologies can perform depend on how sensing, actuation, communication, computing, and intelligence are combined.

To digitally represent a given environment – for example the relevant environment for irrigation – sensors are connected to each other to provide data. This requires communication devices, communication protocols, storage, software to elaborate the data, and actuators. In other words, digital technologies should be understood as **systems**. Moreover, the system of digital technologies interacts with other systems, such as natural and digital ecosystems, social systems and economic systems.

These complexities have been captured by Erickson (2008) who developed a holistic food system framework for capturing complex interactions and feedback between socio-economic and biophysical drivers, and to better understand trade-offs and synergies between nutritional, environmental and distributional/equity outcomes. Typical to food system approaches is the focus of feedback-loops acting as communication and control mechanisms within both natural and socioeconomic systems, referring to processes of information transported forth and back within a system with influence on the outcome (Clancy, 2013; Brouwer *et al.,* 2020).

The multiple interactions are often referred to as complex systems. In a complexity research perspective, different approaches to knowledge, such as positivism, interpretivism, and realism are questioned to provide new insights into assumptions set in existing research (e.g., equilibrium, stability, etc.). To rethink rethinking and improving ways of dealing with complex sociotechnical phenomena (Benbya *et al.,* 2020), complexities can be addressed, for instance, by introducing the concepts of problematisation and responsibilities, using a system approach (Rijswijk *et al.,* 2021).

The urgency of making use of system thinking is increasing lately, due to the rebound effects of hindrances of achieving sustainable solutions, which are systemic responses which can offset the initial intentions (Guzzo *et al.,*

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

2011). System thinking offers the idea to investigate influences across and between factors, and not simply looking at linear evaluation approaches. Understanding systemic impacts of digitalisation can assist the true understanding of transformation towards sustainable digitalisation (Metta, *et al.,* 2022). The literature consists of a range of different system approaches taking different interlinkages into account, including the food system approaches (Clancy, 2013; Brouwer et al. 2020), and for assessing digital agricultural innovations (e.g., Kernecker *et al.,* 2021).

Hence, in this deliverable we specify at a generic level the definition of a system as an 'organised set of elements'; these elements interconnect and interact to perform activities, and these **activities** generate **outputs**.

To carry out these activities, the elements need natural **resources or artifacts,** i.e. human made physical objects. The activities in a system are regulated by **rules,** which regulate the use of resources, the type of actors that can carry out the activities, the interaction among them, etc. Formal rules and regulations, and informal rules, values and norms, which encourage or restrain actors in their activities are referred to as institutions (Ostrom, 2009b). Transformation involves changes in institutional setting, which influence actor's behaviour. A part of rules and resources are generated internally, and system activities contribute to produce and to reproduce them, but part of them are provided or affected by the **system,** which involve feedback-loops, before the activities eventually lead to **outputs** (Figure 2).

Linking digital technology with sustainable digitalisation can thus be done by means of system thinking, assuming complexities, feedback loops and rebound effects. Klerkx *et al.,* (2019) analysed digitalisation as a transformative force in agricultural production systems, value-chains and food systems, providing a thematic overview of highly relevant social science clusters, including: 1) digital agricultural socio-cyber-physical-ecological system conceptualisation, 2) digital agricultural policy processes, 3) digitally enabled agricultural transition pathways, and 4) global geography of digital agriculture development. This included smart farming, precision farming, precision agriculture, decision agriculture, digital agriculture and agriculture 4.0.

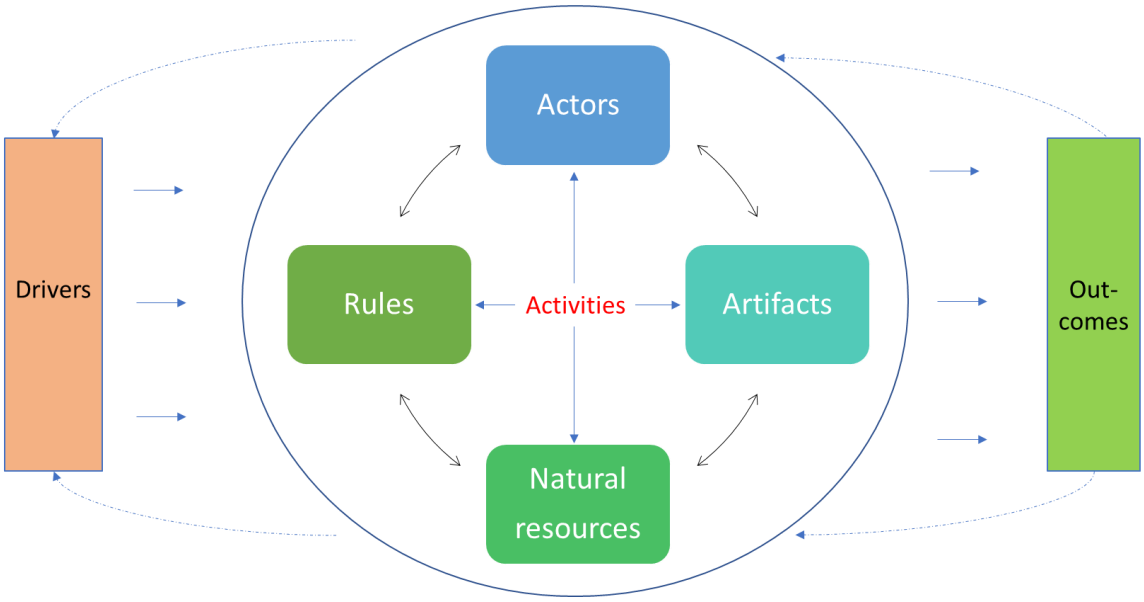


Figure 2 – Simplified system thinking with interactive activities among actors, rules, natural resources and artifacts

As a follow-up, a socio-cyber-physical system was introduced by Rijswijk *et al*. (2021), insisting that the assumption that agricultural innovations is not necessarily a good nor value-free process, particularly when the innovations reinforce non-sustainable current practices and systems, without taking into account socio-ethical implications, digitisation processes may lead to lower-level sustainability. They forwarded the socio-cyber-physical system as a way to understand the relationship between digital technologies and the context they are embedded in using a system approach. They build on what Maye *et al.* (2019) referred to as responsibilisation, which addresses a process involving behavioural standards for involved actors developed and enforced through accounting mechanisms and

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

sanctions, which is fed by problematisation. A socio-cyber-physical system overlaps with a sociotechnical system (Rijswijk *et al.,* 2021). Whereas 'social' refers to social actors, groups, communities and institutions, 'cyber' refers to original digital constructs such as software, big data, cloud computing and IoT, as well as digital reproduction of the physical sphere. "Physical" refers to the natural resources as well as the artificial. When digital technologies are applied to human activities, they become part of broader **socio-technical systems**. To be more precise, referring to **socio-cyber-physical systems**, the elements can belong to the social, physical, and to the digital sphere. The relevance of using the socio-cyber-physical concept is that it helps to predict any change that one sphere will generate into others. Likewise, rules and resources that characterise one sphere can affect the others, in so-called loops.

The concept of **socio-technical system** aims at capturing the hybridity of the situations that characterise social and economic life, and the reciprocal influence between human and non-human components. In the agricultural literature the concept has been used with reference to the actor-network theory (Callon, 1984; Latour, 1987), that allows to interpret the processes of development of socio-technical systems as networks linking together human and non-human, material and immaterial entities that create the structures of everyday life and at the same time build the representations and the meanings upon which actors act. Moreover, the relevance of the concept of socio-cyber-physical system contributes to enhanced understanding of how technologies that can adapt to different contexts and situations. In a large farm, for example, specialised employees perform specific tasks and have access to information related to their domain: in this case, for them it is sufficient to control their domain with a specialised device. In a small farm, a single person needs to be in control of a variety of environments: in this case, she will need a broad range of devices or a multifunctional device.

Metta *et al.* (2022) used the **socio-technical system** to elucidate relationships between the digital and the broader sustainability devilment goals and needs by applying it in a total of 21 living labs. In this way they advance from a linear theory driven approach to a system approach to enhance the understanding of how digitalisation can strengthen the digital transformation towards sustainable digitisation, while dealing with complexities and multiple dimensions, and addressing ethical questions. In assuring responsible digitalisation, they refer to three context specific pillars, referred to as: 1) entities, 2) relationships and 3) activities. Whereas the entities distinguish between the social, cyber and physical domains, relationships refer to how two or more entities are connected within a domain. Activities can refer to all kinds of interactions and actions. The framework is exploratory and is not designed to test pre-defined sets of hypothesis, and as such, not a tool for quantitative impact assessment. Instead, it gives an overview of how to link the digital technologies in transitions towards sustainable digitalisation through a lens fit to a context with complexities, multiple dimensions, feedback loops, and rebound effects.

Responsibility in research on agri-food innovations have also been addressed by Fielke *et al.* (2021) who argue that perspectives of social sciences from various disciplines can contribute to taking care of the future through collective stewardship of science and innovation by critically reflecting on, among others, dynamics of time and scale for digital solutions, challenges of power dynamics and imagination and practices in shaping futures. Notably responsible innovation science is also criticised given the way it is linked with technology assessments, which is not always embraced because of the risk of reducing the role of the technology assessment (Delvenne, 2017).

Linked with the responsible innovation (RI) research is the field of science and technology studies (STS), which is combined with a critical agri-food studies in a special issue edited by Guggang *et al.,* (2023). They look particularly at the roles of powerful actors in policy, industry, technology development and finance and their future vision of food and farming, as well as at instances when agri-food technologies lead to confusion in other food and farming aspects, such as when indoor high-tech trials on plants are returning to the "wild nature". Tomblin and Mogul (2020) introduce the STS thinker skills which involves a reflexive posture oriented towards humility, openness, criticality and action. Ayris *et al.,* (2024) investigate challenges related with use of automatization in agriculture, including rural unemployment, economic and digital inequalities and unsustainable farming practices, by asking the critical questions: who, why and how are stakeholders included in engagement processes in ongoing agricultural robotics development process in the UK? They conclude that only certain types of stakeholders are included, with exclusion often being explained by practical barriers such as language barriers. Also, the engagement strategies include meetings, demonstrations, farm visits, etc., but fail to harness different knowledge types. Often the purposes of engagement are limited to technical sophistication and adoption, and are not addressing ethical questions, among others.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

2.5. Summing up

In this chapter, in order to understand the links between digital technologies and sustainability, we investigated how technologies affect the socio-physical world. First, the term sustainable digitalisation was introduced, which is the overall goal of the activities in CODECS. Motivated by the importance of giving enough emphasis to one of the main risks that are associated with digitalisation, which is inequalities, the CODECS supports the following definition:

Sustainable digitalisation is a process of social transformation by which digital technologies are embodied into socio-economic life to promote intra-generational, inter-generational, inter-species wellbeing, reduce inequalities, and improve the health of ecosystems.

Second, digital technology provision is addressed by referring to a series of concepts, including digitalisation, sensing, actuation, computing and intelligence. It is explained that whereas the process of representing the physical world through numbers is called **digitisation**, the process of digital transformation is thus referred to as **digitalisation**. Moreover, whereas **sensing** refers to the use of sensors in precision agriculture and provides the opportunities to gain large amounts of relatively inexpensive information on the spatial and temporal variation in crops, soil, weeds, diseases, etc, **actuation**, i.e., the action and decision making, executes the decisions made according to the sensing followed by an intelligence process. There is thus a process stemming from sensing going through data and computation, replicated and stored, to intelligence. **Intelligence** refers to when computers can recognise patterns and take action based on data, or at a more basic level, digital intelligence allows the carrying out of tasks such as monitoring, classification, prediction and content generation. After a process of sensing to intelligence, there is a process going from intelligence to actuation, which is when the farmer can make use of the data. This is thus a circular process, because any application also generates more data through sensing.

Third, as a basic system thinking approach, core activities among actors, artifacts, natural resources and rules are put to the centre, influenced and by drivers and outcomes. **Drivers** can be seen in terms of climate and environmental and socio-economic factors which influencing the activities within the system from the outside. **Activities** must be seen in a broader context, referring to activities, interactions, behaviour, communication, etc. **Rules** can also be seen more broadly in terms of institutional factors also covering norms, regulations, governance systems and policy decision making. **Natural resources** refer to ecosystems as well as the natural resources extracted for implementation in our human made system, where also human made capital and technologies are referred to as **artifacts. Actors** refers to individuals, roles, groups, stakeholders etc. All activities taking place give **outputs** in terms of human made production, as well as ecosystem functioning and social well-being among others. This system simplification is thus meant to point to the system factors, which are the influences between the components. Whereas in non-system thinking research takes place focusing on specific components, in a system thinking, the influences between the components are equally important. For instance, the **socio-cyber-physical system** as a way to understand the relationship between digital technologies and the context they are embedded in using a system approach.

Box 3. CODECS – System thinking across Living Labs

System thinking allows us to explore how different elements in a system influences other elements, sometimes in feedback loops. Across the CODECS living labs there are multiple examples of linkages following a system thinking. For instance, the living labs who implement technologies to facilitate communication between farmers and consumers, such as in Poland and Ireland where online market sites with local food are contributing to the farmers in terms of increased income, the wider community benefits from high quality food products and enhanced food security, and at societal level, reduced greenhouse gas emissions and attractiveness of the area to visitors and residents, which are examples of systemic impacts. In Macedonia and Spain, Almeria, enhanced data management communication system at farm level is not only benefitting the farm businesses, but also the environment and biodiversity because of minimised usage of agrochemicals that cause harm. In Spain it is informed that improved food production sustainability - economic, environmentally, and socially – offer increased resilience in the local agricultural sector and create dignified employment and equitably distributed wealth within it.

In the case of animal welfare, in France, not only will farmers have eased workload and increased pig health and welfare on farms, but with a successful example more farmers in the community will decide to make use of the technology, as a strategy to reconnect farming systems and the society. In Latvia, the enhanced animal welfare for beef farming will contribute with a non-intrusive and inexpensive way for specialised semi-natural grasslands farms with high biodiversity to follow strict environmental regulations to strengthen their potential market position, and at community level, contribute to rural development, prevention of outward migration, preservation of biodiversity and the continued provision of environmental services.

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Also for wine makers, systemic factors are important to the living labs, for instance, in Slovenia, not only increased farms' profit, improved business operations and support to work more precisely, efficiently and sustainably will be beneficial, but also the increase in ecological wine production with less pesticide usage, soil protection and CO_2 reduction, as well as preserved bees on finding ways to monitor the queen, with increased bee population as result, will enhance biodiversity in the area and attract tourists in the area, among others. Also, for wine orchards in Greece, Czech Republic and Italy, the new technologies will contribute to environmentally friendly and sustainable alternative by reducing negative effects of pesticides and other agrochemicals, and byimproving water management. Other interesting living lab examples with strong system thinking, includes Hungary contributing with optimised fertilisation based on actual soil information, which also impacts changed habits towards fact-based nutrient management strategies in both small and large farms to make up-to-date, site-specific decisions, and reduced risks in crop production, as well as reduced soil nutrient loss, with an environmental impact for the community. Moreover, in the open farm living lab in France, protection of the environment through improved fertiliser use efficiency, and less environmental impacts related to agricultural practices, network of users, and facilitation of discussions with advisors, are systemic effects of enhanced technology use at farm level. While for the living lab in Latvia/Estonia on grassland management will help the farmers validate their maintenance regimes with evidence of the effectiveness that is measurable, and may increase access to higher subsidies, the effects at community level include an increase biodiversity and improved quality meat production without the addition of fertilisers to fields.

3. A system approach defining costs and benefits

3.1. Introduction

In order to improve the understanding of extents to which a system approach can assist in defining costs and benefits, in this chapter we address costs and benefits generated at different levels. While digital technologies are applied at farm level, sustainability outcomes are observed at a different level; local, regional, even global level (if we consider climate change). The links between different levels need analytic attention given the multi directions of influence and activities following a system thinking approach.

Considering digital technologies as components of broader socio-technical systems implies a deeper understanding of the systemic nature of costs and benefits. Digital technologies disconnect and reconnect elements of the system; new rules and new routines are created; new resources are used, and old resources are abandoned. All these processes need time. A system analysis of costs and benefits, therefore, implies the analysis of; 1) processes of change, 2) intermediate outputs generated along the process, and 3) the distribution of the effects among the system components.

The introduction of digital technologies can improve working conditions, improve productivity, reduce the use of resources, improve animal welfare, reduce environmental risks, etc. In some cases, these effects occur as unintended consequences of action, following rebound effects (Berbel *et al.,* 2015). Moreover, the outcomes of the outputs are transmitted along the value chain, so that system outcomes at farm level can generate costs and benefits for other actors of the chain. Likewise, these effects can spill over in the neighbouring territory, generating other categories of costs and benefits.

The system approach implies the understanding of reality as structured in different levels of complexity. Complexity implies that relationships between components are not linear, as each output can be generated by multiple causes; effects can be both direct, indirect, and retarded; interaction generates feedback and synergies.

In CODECS, three levels of digitalisation have been identified for the analyses:

1. Business processes;
2. Digital ecosystems;
3. Socio-ecological systems.

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

3.2. LEVEL 1. Business processes and digitalisation

Digitisation can be seen as an integration of digital technology, typically comprising both hardware, software, and communication components, into established agricultural processes. For instance, when introducing a digital irrigation system, the following modifications become evident: in terms of actors, the traditional process involving manual irrigation management by farmers shifts to the introduction of automated irrigation control systems, thus reducing the need for certain actors that perform manual activities.

Regarding tasks, the transition includes a shift from the manual monitoring of soil moisture and adjustment of irrigation systems to automated processes driven by real-time data and weather forecasts. Additional resources needed in the digital integration encompass sensors, actuators, and computing devices for data processing, along with potential requirements for training on system operation and maintenance. By dissecting the changes in actors, tasks, and required resources, we can comprehensively analyse the impact of digital technology on established agricultural processes, facilitating better adaptation and optimisation of these processes.

For Sutherland *et al.* (2023) digital technologies are embodied into farm processes as 'assemblages', which is a concept derived from relational philosophy thinking. To focus farm-level change, the authors associate assemblages with a so-called 'triggering change model', for which knowledge is taking part within specific world views, formed by differences in considering territorialisation, historicity and materialities. The conditions for their successful incorporation are related to broader socio-technical systems: infrastructures, complementary devices, specialised actors, specific rules. Farms buy only some components, while other resources (internet connectivity, data, support) are provided as services.

When digital technologies are introduced into an existing business process, they connect and disconnect the elements of the underlying socio-technical system. Digitalisation brings about significant transformative effects (Wohed *et al.,* 2006; Corradini *et al.,* 2018; Marangunić and Granić, 2015). This change extends to various dimensions, including the activities to be performed, the involved actors, and the resources utilised, encompassing technological resources themselves. It is important to systematically capture and understand these alterations to gain insight into the full scope of impact.

(Business) processes are the lowest unit of analysis of CODECS. At this level the digital technologies deploy their effects, and outputs are measured. Processes are (sub-)systems in action. Key elements of processes include:

- Actors: human / animal components of the process;
- Artifacts: physical components of the processes;
- Activities: representing individual tasks or steps that make up a process;
- Events: signifying triggers or occurrences that initiate or conclude activities;
- Gateways: indicating decision points or branching paths in the process flow;
- Flows: representing the movement of information, materials, or resources between activities;
- Resources: identifying the resources required to carry on the process.

Analyses of the changes introduced by digital technologies are thus based on the analyses of a) the system as-is, i.e. the business processes before the introduction of the technology; and b) the system to-be, i.e. after the introduction of the technology (Figure 3).

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

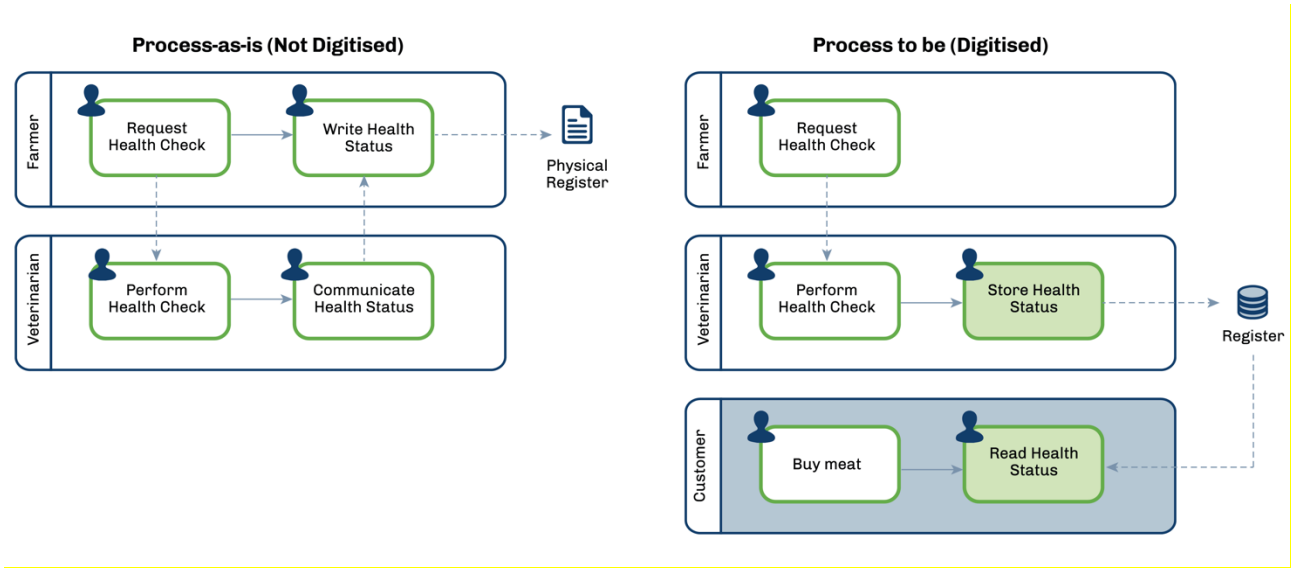


Figure 3 – Business processes before and after organisation at farm level is digitised

Moreover, business process can be analysed from a so-called "goal view" and a "structural view". Whereas the "goal view" represents the objectives addressed by the introduction of the digital technology, "structural view" represents the structural components and relations thereof in the process-to-be. Examples are illustrated in Figure 4.

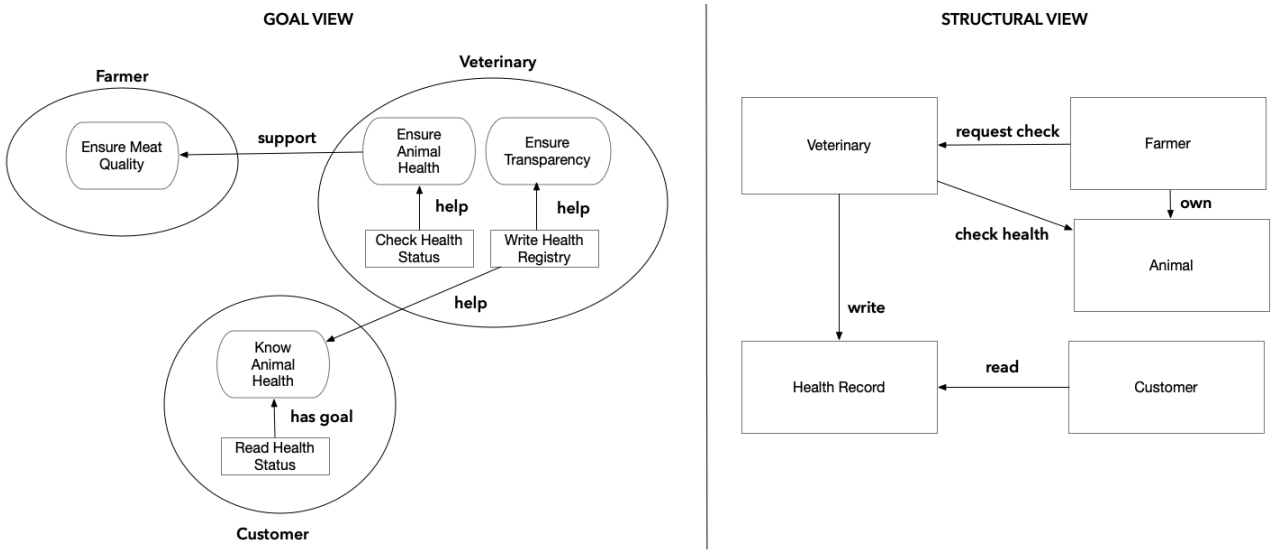


Figure 4 – Goal view and structural view of business processes.

The business process concept is particularly relevant when we consider that digitalisation in agriculture occurs increasingly through provision of services rather than selling of equipment. Business process modelling can help to better understand the costs of digitalisation. Conceptualising digitalisation as adoption of a single technology, in fact, risks not to grasp the complexity of digitalisation, while the attention on the process helps to identify the interaction between users, providers, and intermediaries and to consider all the components of the socio-technical system developed around digital services.

Williams *et al.* (2008) conceptualised a total of 12 leading digital services, including business related services, such as reducing costs, new markets, value-added services and adoption and sale, interaction related services such as mobility, scalability, customisation, optimisation of revenue, human computer interactions (HCI), and technology

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

related including efficiency, bandwidth, evolution, commoditisation and automation. Leimeister *et al.,* (2014) specified that digital services for consumers are highly connected with managerial functions, business strategies, business processes and use of information technology (IT) and product, aiming at users, use and utility objectives. Moreover, they explained how digital services at different stages of industrial society towards information society, and how the digital societies would overlap with existing services. For instance, in a digital society, human related services impacted would include value in context and value in use, task related services would include co-creation and crowd funding, and technology related services would include Internet of things (IoT) and social media. Criado and Gil-Garcia (2019) provides an original approach to the theme of public value generation using smart technologies and strategies in public sector management. They argue that smart technologies, such as AI, combined with strategies having potentials to foster co-creation of public services, can generate public value in management processes based on the collaborative, social and horizontal dimensions of smart technologies. CODECS recognise the different views about digital services in the literature, and is aware of the risks associated with, among others, AI, including the possibilities to fake news by imitating persons in situations not possessed.

Business process level relationships with technology, organisation and technologies. The relationships between technology, organisation and environmental contexts have been addressed in the literature, including by Baker (2012). In his study, the technology context includes all the technologies that are relevant to a firm, such as those which potentially could be used because they are available in the market. The reasoning of including all these technologies is based on the thinking that there is a limitation of use based on what technologies exist at a certain time. Baker (2012) refers to a second level as the organisational context. At this level both formal and informal factors are influential to adoption of technologies for a firm. The characteristics and resources of the firm are then put central. This includes informal practices of communication and responsibilities, as well as more formalised structures of employees, intra-firm communication processes, firm size, and slack resources. Also, informal linkage agents, may influence attitudes of the firm by referring to positive or negative argumentation of use or no use. At a third level Baker (2012) refers to the environmental context, which to him is specified as industry characteristics and market structure, technology support infra structure and government regulation. Because this is highly confused with the natural environment in a multidisciplinary setting, we replace “the environment” with “the surroundings” in the following.

Comparing the business process level introduced in CODECS with Baker (2012), especially the technology context is similar. Notably, CODECS refers to scaling readiness of the technologies (Damtew *et al.* 2023; Sartas *et al.,* 2020). Also, the firm is the unit of organisation at the business process level, which is highly influenced by technologies (Figures 3 and 4). Note that it is emphasised in CODECS that business processes are highly influenced by factors such as veterinary health checks and advisers, who again are influenced by the customers (Figure 3). As such, some of the external factors in the environmental context as described by Baker (2012) are considered in the business process level.

However, because “the environment” the way it is described by Baker (2012) is seen very limited excluding factors like the digital and natural environment contexts, as well as governance, in CODECS we have defined two more levels. To be able to account for societal, economic and environmental costs and benefits in a broader sense, it is seen critically important to CODECS to deal with the complexities when addressing costs and benefits, rather than to simply referring to market, infrastructure and regulations. Notably, this becomes more visibly when we reach the higher levels of digitalisation level 2: Digital ecosystems and level 3: Socio-ecological systems (SES).

For this deliverable the understanding of readiness factors is emphasised at level 1: Business processes level. While Baker (2012) refers to a decision-making process, in CODECS we refer to the readiness of a farmer to adopt the technology. Looking at the readiness factors across the interdisciplinary literature, reference to the factors influencing the farmers behaviour include motivation, capabilities and opportunities (McCampbell *et al.* (2023). These are personal characteristics of a farmer, while the scaling readiness refers to the characteristics of the technologies. When the two readiness categories are combined, we refer to this as system readiness (Figure 5).

Box 4. CODECS – Services across Living Labs

The services provided by the many living labs in CODECS cover a series of different categories, including services like online information provision, animal welfare for sheep and beef, as well as ensuring a good plant environment, particularly in greenhouses, in vineyards and on the field.

CODECS has received funding from the European Union’s Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

In the case of online information provision, in Poland, targeting consumers, the service of local marketing provides an online platform for building local markets for locally-produced food based on direct buying/selling of participating producers and consumers, whereas in Ireland an online site provides information about sourcing healthy and locally produced food in support of local economies and the diversification of rural livelihoods, as well as need for local ownership of food system infrastructure by producers, eaters and local enterprises. Similarly, in Scotland the living lab provides an online digital tool for boosting small farms' capacity to take advantage of these resources in a way that fits their everyday practices, to develop a supportive environment for knowledge exchange and peer-to-peer learning. In Germany the online site offers learning material for farmers and students on how application of digital technologies in crop production can increase sustainability of farming practices in the field, on farm and through regional value chains, and provides a basis for further development in dialog with vocational teachers and farmers. In Macedonia an online tool is a communication system which provides services in terms advising on how to deal with challenges of limited agricultural professional support, deficiency of farm accountancy and agro-technical operation data, non-optimised agricultural production (inputs and processes), and energy inefficiency, among others.

Some of the living labs offer services in terms of animal welfare. This includes sheep farming in Italy to ensure health monitoring to increase efficiency of cheese making and sheep management, and in France, to enhance sheep welfare to measure production data of each milking, monitoring of sheep evolution, definition of alerts and measurement of T°, humidity, and weather environment parameters. Also, in France, for pig welfare, the technologies are not predefined, but will be co-created for each demo farm, by listening to their stories about needs of technologies, and participating / organising the demonstration. In Latvia, the services justify higher environmental standards of the premium local products demanded in the local market, to comply with a misunderstanding of beef production in Latvia.

Ensuring a good plant environment is an overarching service to many living labs. Ensuring good conditions in greenhouses, such as in Serbia, gives possibility for monitoring of soil nutrients for fertilisation prescription to increase yield and prevent damage and plant stress induced by low or high temperatures. In Spain, enhanced integration of heterogeneous data from different sources will increase interoperability to allow enhanced management and optimisation of resources, which allows for more sustainable natural resource management techniques, food security and healthy environment. In the Check Republic, a plant environment is ensured by reduced use of water/ pesticides, optimal spraying, reduce risk of spring frost impacts, ensure sufficient pollination, and increase effectiveness of fruit crop harvesting, production and overall business management.

A series of livin labs are in particular concentrated on plant environments in vineyards, such as in Italy where they adopt adequate irrigation practices, reduce water quantities as well as pesticides and chemical products to improve the yield and the quality of organic table grape production, and reducing labour intensity and production costs. In Slovenia, the services contribute to reducing use of water and pesticides in the winegrowing process, protect bees and preserves healthy biodiversity, lower CO_2 emissions (less treatments in the vineyards and less control of the hives), and save time and improve farm profitability. In France the digital technologies proved services to detect dysfunctions in the vineyard at an earlier stage, to adapt technical itineraries and to limit the effect of climate change to preserve the typicality of the wines.

Ensuring a good plant environment in the field is particularly relevant in Belgium, where they make use of drones and AI to spray more precise to reduce use of herbicides/ pesticides and increase productivity with the help of crop protection. In Latvia, drones can capture the changes in the grassland, i.e., reduced density of trees in overgrown meadows, reduced expansive species, and improved biomass production in a cultivated meadow from over sowing with legumes. In Slovakia, the services ensure high water and soil qualities by determining the amount of water a crop needs based on monitoring soil water availability, rainfall during the growing season, stages of crop growth, crop rooting depth, and environmental factors including sunlight, humidity, temperature, and wind speed. In Greece, plant protection products (PPPs) are used for open-field crops, including vegetables, orchards and vineyards, and arable crops to protect crops against pests, weeds and diseases, and to ensure productive, profitable and sustainable agriculture. In Hungary, the services optimise nutrient management and crop production to enhance sustainability by analysing nutrients in soil in a fast, affordable and reliable way.

The role of readiness for adoption of technologies. The literature gives clues about causes to sometimes slow adoption of precision agriculture, for instance, Lowenberg-DeBoer and Erickson (2019) refer to biased farmers' perceptions, which often narrow precision farming to only covering variable rate technologies not considering other options, whereas a big gap is identified with the medium- and small scale farmers in the developing world who have no access to it. Barnes *et al.* (2019) estimated the difference between adopters and non-adopters of precision agricultural technologies, by using the variables categories into; socio-economic characteristics (e.g. age, education), structural and financial characteristics (e.g. size, income, labour), current technological adoption using a scale to (0 to 4), attitudinal characteristics (e.g. positive, uncertain), informational characteristics (e.g. advisor, farmer), and institutional characteristics (e.g. management). This analysis provides on a large scale, the cross-regional attitudes and perceptions towards technology uptake providing a better understanding of common barriers between adopters and non-adopters across countries in Europe, which can be used to identify potential public

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

interventions to encourage more adoption. Such support can be in the form of direct subsidies, promises of cost reduction, tax reduction, capacity building, etc. Gabriel and Gandorfer (2023) analysed adoption of precision agriculture particularly by small scale farmers. Their approach is based on three groups of variables, including 1) context specific application variable in the agricultural sector, 2) adaptive query of sector specific technologies linked with current use and non-use, planning over a period of 5 years, and entry technology, and 3) multiple usage of technologies and sequential adoption over time. For promotion of digitalisation, they argue it is critically important to know the trends of uptake of equipment and technologies by the small-scale farmers for strengthening of the policy efforts. To deepen our understanding, the concept of process helps to revise the notion of adoption, which gives a static representation of innovation, and introduces the dynamics of socio-technical change of digitalisation.

Successful digitalisation depends on the interaction between users and technologies within a specific application context. This interaction depends on user and on scaling readiness. U**ser readiness** is users' ability to use the technology in a meaningful way, and **scaling readiness** is a property of the technology which depends on its design in relation to the characteristics of the application scenario (Damtew *et al.* 2023; Sartas *et al.,* 2020).

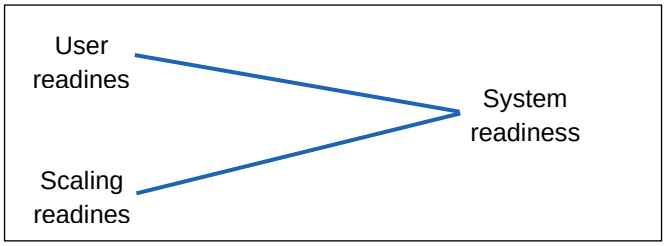


Figure 5 – User, scaling, and system readiness

User readiness. Users participate in business processes to pursue their goals: income, curiosity, respect of contractual relations, learning, etc. In doing this, they mobilise their skills, knowledge, physical strength, as well as their motivation in relation to given opportunities. Balafoutis *et al.,* (2020) analysed trends of adoption readiness jointly with economic, environmental and labour factors for smart farming technologies. For the economic, environmental and labour factors, a long list of variables is included. The economic factors include variables like productivity, revenue, costs, energy use and waste, the environmental factors include variables like biodiversity, use of water, fertiliser and pesticides, emissions, and disease pressure, while the labour factors involve variables like labour time, farmer's stress, heavy labour, workers illnesses and accidents. In this article, clear links are made between challenges faced by farmers and relevant smart farming technologies that can contribute to solving the challenges. The challenge categories include: 1) resource efficiency of e.g. water, nutrients, pesticides and labour, 2) management/prevention of diseases, weeds, etc., 3) risk management with regards to food safety, pesticides, emissions, 4) compliance with legislation and standards, and 5) collaboration across the supply chain. For instance, the challenge of resource efficiency of e.g., water, nutrients, pesticides and labour, can be dealt with by use of sensors, big data analytic tools, Decision Support Systems, etc.

McCampbell *et al.* (2023) builds on behavioural theory for operationalisation of user readiness, referred to as so-called COM-B model. In such a model, C refers to capabilities, O refers to opportunities and M refers to motivation, whereas B refers to behaviour. The user readiness components explaining the COM (Michie *et al.* 2014; McCampell *et al.* 2023) include:

- Physical capability, such as physical skills, strength and stamina, explaining for instance the state of a farmers' physical ability and skills to use a digital device.
- Psychological capability, such as knowledge or psychological skills and stamina to engage in the mental process, explaining the education/literacy levels and previous experience with using digital technology.
- Physical opportunity, such as environment affording opportunity by means of time, (economic) resources, locations, cues, explaining for instance the organisation of the (digital) extension system, the (economic) resources available, and the (digital) infrastructure.

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

- Social opportunity, such as ways in which farmers 'think', farmer's mindset, affording opportunity by means of interpersonal influences, social cues, cultural norms and values, explaining for instance gender norms in farming communities, mindsets about digital technology and agricultural extension and social interaction in farmer communities.
- Reflective motivation, such as processes involving plans (self-conscious intentions) and evaluations (e.g. beliefs, norms, goals, values about good/bad), explaining for instance perceived government enforcement mechanisms, experienced norms and beliefs about agriculture and digital technology, innovativeness of farmer and future goals of farmer.
- Automatic motivation, such as processes involving emotional reactions, desires (wants/needs), impulses, reflexes, explain for instance perceived needs and demands and expressed interests.

In Figure 6, the COM components are conceptualised visually, which may continuously vary over time, specified to context relevant variables which can be quantified. It is advised that optimal user readiness for a digital technology is located at the overlap of capability, opportunity, and motivation.

One of the factors leading to increased capabilities and hence enhanced user readiness is the digital skill factor. Vourikari *et al.,* (2022) developed an advanced version of the EU wide Digital Skill Indicator, responding to digital competence as one of the eight competence essentials for all individual in a knowledge-based society. This includes a total of five competence areas, including: 1) information and data, 2) communication and collaboration, 3) digital content creation, 4) safety, and 5) problem solving. Skills corresponds to knowledge, which brings us to the concept of Agricultural Knowledge and Innovation System (AKIS).

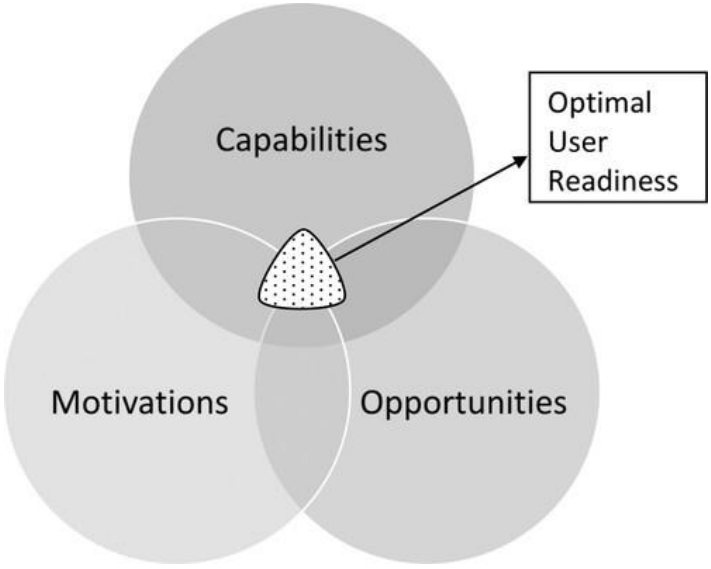


Figure 6 – The determinants of user readiness (source: McCampbell et al. 2023)

Technologies can have various levels of fitness to the application context, as for example they can be an adaptation of technologies generated in other sectors. The adaptation of a given technology to a specific application scenario implies adaptation of design, hardware, and software. On this regard, we can speak of **technological scaling readiness**. Technological scaling readiness is referred to the compatibility of the technology with the existing application scenario. Scaling readiness provides action-oriented assessment support of a total of five main steps proposed for informed scaling processes, including; 1) to characterise profile of stakeholders, innovations and innovation systems, 2) to diagnose current readiness to scale in the specific context, 3) to strategize by developing strategies to overcome bottlenecks for scaling, 4) to validate, facilitate and negotiate scaling processes and multi-stakeholder involvement, and 5) to navigate and monitor the implementation process to allow for adaptive management. Scaling readiness is designed to deal with emergent and unpredictable processes of change.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

The interaction between user readiness and scaling readiness characterises the **system readiness** (Figure 6), which can be regarded as the capability of a system and can be defined as 'the power of a (socio-technical) system to achieve a given goal through a process'. The capability of a system, thus, is not just the sum of individual characteristics, but is a systemic quality that involves the flows between the elements, including feedback loops and rebound effects. For example, farmers could reduce water consumption due to digital technologies, but if reduced water costs increase the use of water at regional level, the sustainability effect will be negative. This is what in the literature is called rebound effect (Berbel *et al.,* 2015). Generation and adaptation of system readiness to the specific contexts hence depends on the characteristics of the broader digital ecosystems and socio-ecological system (SES).

The assessment of system readiness is thus related to the goals that the system is supposed to achieve. The goals set by the entrepreneur could be different from those of the workers, the local community, or the broader society. This aspect is reflected in the assessment of the costs and the benefits.

System readiness can also refer to whether an innovation has been validated and tested for the purpose it is meant to play in the society (Damtew *et al.,* 2023). For a transition with societal change towards sustainable digitalisation, scaling of innovations is critical (Sartas *et al.,* 2020). With scaling, others than the existing group using the innovations get involved. When developing, testing and validating innovations targeting the SDGs, the scaling of innovations is particularly relevant. Whereas scaling often is referred to as more research and development programs, projects and interventions which must deal with context specific bottlenecks to reach scaling for a particular innovation, such approach is not dealing with complexities. In order to reflect critically on how ready innovations are for scaling in specific spatial and temporal contexts and what the appropriate actions would be in a complex setting to accelerate innovations, the scaling readiness approach has been introduced (*ibid.).*

3.3. LEVEL 2: Digital ecosystems

External conditions for successful farm digitalisation are analysed in CODECS as 'digital ecosystems'. The concept of digital ecosystem reflects a system approach, but stresses that the type of system considered is a 'living' system, made by interacting components that co-evolve and adapt to the environment by learning. In an ecosystem, components compete for the use of resources, and at the same time cooperate, sharing resources and establishing common activities, routines, and infrastructures. Moreover, the outputs produced in an ecosystem can be combined to create innovative goods and services (Sutherland *et al.,* 2012). At a digital ecosystem level, the technology, organisation, surroundings framework introduced by Baker (2012) becomes less relevant, because organisation does not refer to one firm, but rather the interrelationship with other firms, data, information and actors in interconnected manners, and technologies are not limited to what is in reach by a farmer but address the interlinkages and digital capacities at a large scale. Digital ecosystems are not about decision making of one farmer, but about support to production, storage, communication, and use of digital technologies and data. The surroundings as described by Baker (2012) is still relevant to some extent at this digital ecosystem level, but in CODECS the surroundings also refer to digital, social-economic, organisational, and physical components. Because the natural environment is yet not addressed sufficiently, there is a third level in CODECS, referred to as the socio-ecological level (SES), where also the governance system is addressed in ways that are not too simplistic to understand the costs and benefits from a system thinking approach at a regional scale (Section 3.5).

Defining digital ecosystem. The literature is rich on definitions of digital ecosystems. The term 'ecosystem' was coined in the early 1930s by the British botanist Arthur Roy Clapham at the request of the ecologist Arthur Tansley who used the term to draw attention to the importance of transfers of materials between organisms and their environment (Willis, 1997). Ecosystem now commonly refers to a complex network or interconnected system, and the term is widely used in discussions of software developments, stakeholder management, innovation, and business strategies (Wolfert *et al.,* 2021). Digital ecosystems provide a mechanism to bring players together […], and the digital ecosystem is part of a socio-technical system, which means that not only the software is important, but in particular, the players and their relationships with each other are central (Falcão, 2023). Digital ecosystems are also described as socio-technical infrastructures and processes bridging the different disciplines of social science, computer science, and natural science together (Amritesh, 2010). Moreover, digital ecosystems have been motivated by the convergence of three networks; ICT networks, social networks, and knowledge networks, which

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

are comprised as a structure that connects and mobilises areas of study and networks (EU, 2007). The literature also explains digital ecosystems to cover four scientific disciplines: social, economic, engineering / computer, and natural sciences (Koch, 2022). Furthermore, the informal organisation of a digital ecosystem is about the unwritten rules that influence the social interaction and trust between the stakeholders, including cultural and ethical considerations (Wolfert, 2023).

Whereas digital ecosystems are ecosystems where digital technologies mediate and affect the relationships among entities in order to perform a vast array of functionalities (Metta, 2018), it is also explained as a social system which needs to deal with heterogeneity and greater variations in actor's abilities and resources to participate in the network (Rajagopalan, 2008). The digital ecosystem entails interconnected and intra-dependant digital platforms, created at key institutional levels (international, national and local/community) augmented by technical (ICT) and social networking processes that help break down barriers to both horizontal and vertical knowledge sharing (Sarkar, 2007). In context of knowledge transfer and learning, a digital ecosystem can be viewed as a socio-technical system which supports knowledge creation, recreation, diffusion, absorption, and exchanges that support the dynamics of social innovation (Amritesh, 2010).

Against this background, **CODECS defines digital ecosystems as an organised set of digital, social-economic, organisational, and physical components that support the production, storage, communication, and use of digital technologies and data.**

Disentangle digital ecosystems. According to Iansiti and Levien (2004), a business ecosystem's health can be measured along three different dimensions; 1) productivity, 2) robustness and 3) niche creation. Whereas productivity is seen the most important, for which the ability to effectively convert nonbiological inputs, such as sunlight and mineral nutrients, into living outputs, robustness refers to the durability of the benefits. Because it is also important to exhibit variety and support diversity, the third measure of health is referred to as niche creation.

Iansiti and Richards (2006) addressed some core bottlenecks for advancing digital transformation in the financial service, which included cultural factors such as resistance to change, as well as the pandemic and lasting recession concerns. More precisely for financial service organisations, the main hurdles included: 1) effective allocation of resources to the right transformational areas, 2) embracement of digital transformation across the entire organisation, 3) support to continuous learning, 4) alignment of digital transformation with business objectives, 5) securing top talent to support digital initiatives, and 6) acquiring of necessary resources to effect digital transformation, etc.

The characteristics of digital ecosystems can be explained in relation to **external (to farm) drivers of digitalisation**, which explain the extent to which the digital ecosystem can facilitate the successful adoption of digital technologies (Wolfert *et al.,* 2017) (Table 1).

Table 1 – Characteristics of a digital ecosystem

External drivers	Characteristics linked to the ecosystems
Social/ cultural	Trust, cooperation, communication, conflict resolution
Technical/ technological	Connectivity, interoperability, intensity of data flows
Economic/ financial	Transaction costs, power distribution, trust
Environmental	Ecosystem integrity, diversity, connectivity
Political	Communality of values and interests, institutional cohesion

Digital ecosystems provide the conditions - opportunities and constraints - for the successful digitalisation of agricultural processes. These conditions can be analysed with the concept of **conduciveness**. **Digital ecosystem**

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

conduciveness refers to the extent to which the context supports the growth and success of digital activities, such as the development of new technologies, the creation of new businesses, and the adoption of digital solutions.

Box 5. CODECS – Examples of conduciveness issues across Living labs

In CODECS, conduciveness can be enhanced in three different manners; 1) by employing the new technology itself, 2) by filling the gap of low capabilities and readiness level at farm level by providing capacity building and training, and 3) by impacting the community broadly speaking in ways that give the farmer secondary benefits in terms of enhanced infrastructure and market opportunities for further growth.

First, technology can contribute to enhancing conduciveness, for instance, in Poland when new distribution channels as part of the local market for locally produced food increase demand from the local market, more food processing takes place at the farm level and administrative burden gets reduced, conduciveness is enhanced at farm level. Also, in Italy, the technology can contribute to enhance conduciveness by making the sheep farming easier and thus attract young people, and when optimisation of the conditions in the greenhouses in Serbia allow remotely and timely reach to monitor temperature and humidity and hence enhances the conduciveness for the growth of plants, and conduciveness to the farmer who obtains more time for social life and possibly improved health. Also, in Italy the technology provides tools to effectively manage the production by enhancing conduciveness through monitoring of pesticides and water use.

Second, conduciveness can also refer to different types of support that is needed to actually be able to make use of the possibilities with new technologies, which is unclear exactly what it is across the living labs but could refer to financial and informative support. In the German living lab, the target is to fill such gap, by enhancing conduciveness through increasing capacity building and learning of farmers online to assist them in reaching readiness levels to benefit from the technology.

Third, conduciveness in a system thinking can show that when technology is used at farm level, positive consequences can be obtained at community level, which again will impact the farmer conduciveness positively. This is referred to as a typical feedback loop. For instance, in the living lab in Slovenia, farmers improve their business operations, which also has a positive impact at community level, with more economically viable farms, more jobs, more female in the business, more tourists in the area, which all can enhance conduciveness at farm level by improved infrastructure and widen potential markets.

A diversity of ecosystem perspectives. The World Economic Forum (Jacobides *et al.,* 2019) introduces the concepts of Digital platforms and ecosystems, referring to the fourth industrial revolution which enables new digital and physical technologies with huge implications of the economy and the society. The digital platforms are influencing and dominating our lives as consumers, employees, community members and citizens, initiatives which according to the authors aim for broad collaboration between public and private sectors, between corporate giants and start-ups, and with consumer rights groups and civil society. Significant societal changes influence diversity in micro-macro levels, affecting commercial and financial models, as well as employment, social and regulatory issues. Examples show “network” effects where measuring successes as scaling effects with numbers of users in a community, orchestration of value creation by outside users, the role of customers and private partners in delivering policy objectives, collaboration in an ever-interconnected digital world, the opportunities for making use of multiple skills, assets and expertise an ecosystem offers. The result is a shifting landscape of trust and a fundamental redefinition of institutional and societal governance. Notably, digital platforms are a very complex topic, which will need further investigation about how digital platforms are connected or interdepended with digital ecosystems, and how this will vary according to which theoretical perspective is used. This also applies to the term network, because it matters tremendously whether you refer to a technical, social media network or to a social network that may exist in a neighbourhood.

The literature addresses many different types of ecosystems, including knowledge ecosystems. In a study by Valkokari (2015), a comparison of characteristics of business ecosystem, innovation ecosystems and knowledge ecosystems are made. Whereas the knowledge ecosystems are based on knowledge exploration, the innovation ecosystems are based on co-creation and business ecosystem on resource exploitation for customers value. The knowledge ecosystems are based on decentralised and distributed nodes and synergies through knowledge exchange, while the business ecosystem is based on global competitive and cooperative business relationships and the innovative ecosystems are based on different levels of collaboration and openness among geographically clustered actors. The actors in a knowledge ecosystem are research institutes, innovators, and technology entrepreneurs providing knowledge nodes who are grouped around knowledge exchange or non-propetarian resources for the benefits of all actors, whilst business ecosystems involve suppliers, customers and focal companies operating as a platform sharing resources, assets and benefits and may aggregate other actors in

Funded by the European Union

CODECS has received funding from the European Union’s Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

networked business operations. The innovation ecosystem involves innovation policy makers, local intermediators, innovation brokers and funding organisations, who geographically proximate actors interacting around hubs facilitated by intermediating actors. The three types of ecosystems may overlap, for instance, in a focal company or platform.

First, digital business ecosystem is a collaborative network with different entities that co-create value through information and ICTs, building on the advantages of digital technology (Senyo *et al.,* 2019). The aim in this research is to define research themes, methodologies, and theories and gaps of the digital business ecosystems. The central research themes are; 1) business issues, such network analyses, value-chain co-creation, governance, legal issues, trust and risks, 2) technical issues such as platform design, process of service design and technologies, 3) conceptualisation of digital ecosystem issues such as development, management, and projects, and 4) artefacts such as digital ecosystem methodologies, frameworks, and models. The main categories of research include quantitative, qualitative and conceptual oriented methodologies and methods, whereas theories consist of a long list, including for instance, ecology theory, complex network theory and transaction cost theory. By applying the approach recommended, the authors intend to enhance further integration of a series of studies taking place in the field of digital business ecosystems.

Second, Maroufkhani *et al.,* (2018) introduce the entrepreneurial ecosystem, which refers to a context of social cultural and institutional factors and a policy context creating a conducive environment for which a risk-taking entrepreneur seeking to create value and thus contribute with economic growth. Entrepreneurship is a profit-making process, which can contribute successfully to both the economy and the society, depending on the appropriateness of support provided by the entrepreneurial ecosystem. The successes of entrepreneurship and the capabilities of entrepreneurs contribute to the prosperity of economic development in terms of innovation, knowledge base economies and national competitiveness policies. More precisely, an entrepreneurial ecosystem serves the entrepreneurs by successful interaction with markets, policies, industrial dynamics, crowdfunding, societal support (e.g. infrastructure), culture, human capital and finance.

Third, business ecosystems are defined more broadly. According to Peltoniemi and Vuori (2004), a business ecosystem has a strong link with complexity theory and has a lot of analogies with biological ecosystems. The analogy of the business ecosystem and the biological ecosystem facilitates the understanding of some that internal capacities are interrelated with the overall ecosystem's health, and the importance of understanding the interdependencies, integration, the role of employing ecosystems more than individual companies, and the implications of taking action without understanding the impact (Iansiti and Levien, 2004). Notably, this is not in overall agreement with all CODECS project partners. Moreover, its main components consist of industrial ecosystem, economy as an ecosystem, digital ecosystems and social ecosystems. Because of its complexity, it is reliant on discussing views and adaptive systems, they are self-organised, emergent, and based on co-evolution. Within a business ecosystem, core domains of the IT ecosystem exist that include hardware, software, connectors, internet, media, and services (Iansiti and Richards, 2006). In a framework for analysing health and performances of a business ecosystem, robustness, productivity, and innovation are used as the core concepts of reference. Robustness is a quality for providing durable benefits for members and consumers of the business ecosystem, which depends on the sustainability of the ecosystem, and its financial betas and firm survival rate. Productivity in business contexts of constantly changing conditions, with new technologies, new processes, new demands, and new competition, refers to the ecosystem of today, as well as converting raw materials and value-creation into lowered costs and new products through innovation. Innovation and niche creation refers to the ability to capturing the diversity of types of organisations, as well as alternatives and choices. This points to the fact that AKIS may or may not have commonalities and overlaps with digital ecosystems, depending on the context

Does Agricultural Knowledge and Innovation Systems (AKIS) have commonalities with digital ecosystems? Key drivers of the development of conducive digital ecosystem are multi-actor innovation networks. Through interaction, these networks co-develop solutions to users' needs tailored to specific contexts, and at the same time contribute to the structuration of the digital ecosystems.

A focus on knowledge and innovation related infrastructures and processes in the digital ecosystem can be oriented with the application of the Agricultural Knowledge and Innovation System (AKIS) concept. In CODECS an interesting discussion takes place on linking AKIS with digital ecosystems, and also, linking digital ecosystems with the Socio-Ecological System thinking. Whereas it is not possible to argue that AKIS itself is a digital ecosystem, it is evident

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

that AKIS in different ways across Europe is influential in shaping digital ecosystems, and institutional settings. AKIS elements, such as institutional settings for knowledge exchange and dissemination, impact the building and linking of eminent institutional features of the digital ecosystems. For instance, in some countries, farmer organisations may act as a barrier to the conduciveness of a digital ecosystem because they are the owners and contributors of data, which give them power to resist to digitalise in a role of data intermediators. In linking digital ecosystems to the socio-ecological system, it appears to be three different views, for which one view still is based on a business entrepreneur view to digital ecosystems, another view is more inspired by the innovation system perspectives and one more in line with a macro and environmental level view. In CODECS, the three levels have been defined, for which digital ecosystems fulfils a level between the business process at a lowest level, and the socio-ecological system level at a higher level. AKIS is considered a partly overlapping subsystem, parallel to the digital ecosystem, and both are considered subsystems to the socio-ecological system. In the following we address this concept in the context of digitalisation and follow up with a broader scope of digital ecosystems based on the literature and briefly suggest core assessment criteria.

The **Agricultural Knowledge and Innovation System (AKIS)** concept has become an important avenue for studying the structure and the evolution of knowledge and innovation-related infrastructures and procedures (Knierim and Birke 2023). Since recently, the concept has also been used to better frame a new field of activities in the Common Agricultural Policies (CAP) where it is 'defined as combined organisation and knowledge flows between persons, organisations and institutions who use and produce knowledge for agriculture and interrelated fields' *(Reg 2021/2115)*. Frequently, the AKIS is considered an entity, a network that links people and institutions to promote mutual learning and to generate, share, and utilise agriculture related technology, knowledge, and information (SCAR AKIS 2012; 2016), Nevertheless, because systems in general, and knowledge and innovation systems in particular, are mental models or symbolic constructions, it is important to keep in mind that any AKIS should be considered a snapshot, or a spotlight on a certain actors' constellation, or a description of a series of interactions and collaborations etc., and not as 'real' (Birke *et al,* 2022). As such, the AKIS concept has an important potential to enhance our understanding of complex interactions and interdependencies relevant to learning and behavioural change, and thus, is likely to contribute to the improvement of conduciveness of a digital ecosystem.

The promotion of the AKIS concepts is two folded intending: 1) to foster transition towards a stronger co-ordination between a broad range of actors in AKIS despite a difference in national institutions, and 2) to ensure funding mechanisms and scope and nature of research (Moreddu and Poppe, 2013). The actors in the AKIS, which are directly relevant for agricultural innovation in the food chain, are presented in Figure 6.

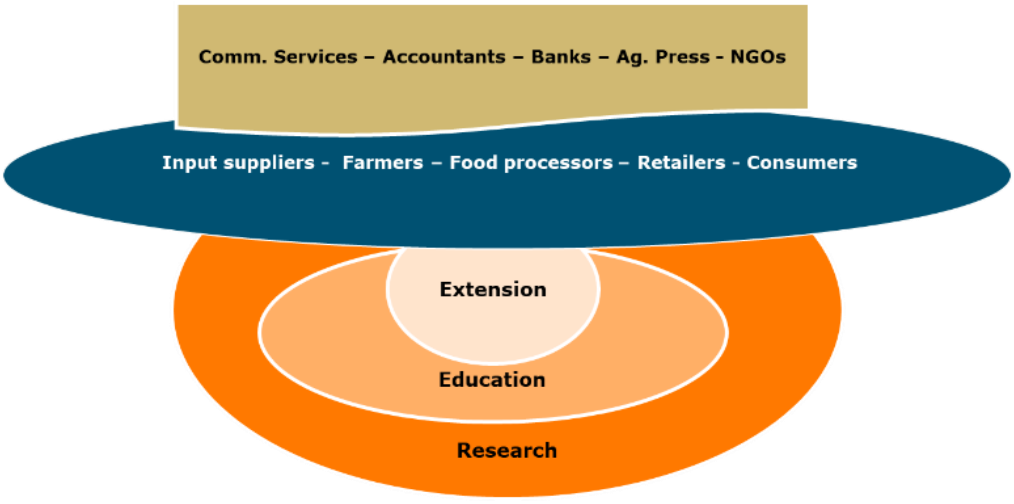


Figure 7 – Actors in the AKIS that are directly relevant for agricultural innovation in the food chain (Adopted from SCAR AKIS -2012: 9)

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

On the one hand, the AKIS concept is central in differentiating and operationalising the knowledge and innovation related strategies for strengthening advisory services for farmers (EU-SCAR, 2015), and on the other hand, AKIS refers to complex arrangements and interaction between all the AKIS actors, knowledge institutions and informal networks (EU-SCAR, 2013).

Current EU policies intend to strengthen countries' AKIS infrastructures and related activities through knowledge and innovation targeting interventions, coordination bodies and mechanisms and resources. One example for such institutional changes consists of clustering capacities at regional level by setting up centres for technology convergences, reinforcements of multidisciplinary, linking research and business and public private partnership as strategies to achieve more efficiency, through co-financing, co-operation, co-developments, co-innovation, and cross border collaboration (Moreddu and Poppe, 2013). Although there is no 'one' AKIS, because they differ across contexts and systems and are formed in the minds of the various actors, they are settled into a broad range of institutional settings influenced by globalisation, increasing competitiveness, and increasing sizes of farms and agri-business, as well as societal concerns about the environmental, animal welfare, biosecurity and food related health issues like obesities (Knierim et al. 2015, OECD 2015). EU member states are expected to formulate strategic objectives for their agricultural policies, including some referring to the maintenance and the enhancement of AKIS structures and measures (EU Reg 2021/2115). As there is no single way to achieve common objectives, and to improve efficiency and relevance of AKIS through transitions at macro-level, governments must address market fundamentals, open trade and investment policy, competition, clearer and simpler regulations, education, research and acceptance of the society, which all are related with agricultural innovations which would benefit from improved knowledge infrastructure and research.

The AKIS concept offers with the procedural perspective an entry point to analyse innovation processes with a network perspective, emphasising that innovations frequently emerge from communication and collaboration of a diversity of actors and rely on joint exploration, learning and experimentation (Moschitz *et al.,* 2015; Wielinga *et al.,* 2017).

With the philosophy that change is triggered at microlevel, Sutherland *et al. (*2012) proposed the so-called "Triggering Change Model", including five circular stages of; 1) path dependency, 2) trigger events, 3) active assessment, 4) implementation and 5) consolidation. This approach helps to understand transformative processes from a micro perspective, and highlights options for new forms of cooperation, such as across cooperatives and technology providers. Sutherland *et al.* (2023) advanced the understanding of AKIS by means of a so-called assemblage perspective, referring to territorialisation, historicity and materialities, focusing particularly on the role of knowledge within these aspects. Territorialisation refers to processes of inclusion and exclusion through formation of formal and informal rules, whereas historicity refers to how history is currently perceived and understood as influencing the present. Material elements are assumed to have agencies associated with their material characteristics. Further, conducting research of assembly theory combined with AKIS, unravel issues of co-construction and co-learning of farmer knowledge and associated processes, and highlights different types of expertise, as well as inequalities between farmers in their access to knowledge.

An agri-ecological perspective refers to farming practices based on leveraging principles of ecology and preserving nature, which is central particularly in policy making in France (Coquil *et al.,* 2018). Employing a system thinking, it is illustrated how interactions with AKIS actors and peers influence norms, references and information, leading to elaborations of decisions, influencing agricultural practices and elaborated production. It is further illustrated how interactions with AKIS stakeholders influence conceptual and practice dimensions of action and knowledge, as well as professional norms, which are framing the farming systems in the farms daily work, together with the values debated broadly in the society. Thus, the AKIS concept can be a useful tool to guide the identification and classification of stakeholders and actors with a territorial, a sectoral or value-chain focus.

The AKIS perspective creates awareness for the knowledge resources necessary to farm digitalisation, which can hence be regarded objects of the digital transformation, given that digitalisation changes the processes of knowledge circulation, and potential drivers of digitalisation. As such, AKIS related interventions and measures can take a role as both enablers and barriers to ensuring a subtle conduciveness environment of the digital ecosystem. However, because of the challenges of catching up with, among others, the twin transition of digital and ecological, there is a risk that a lag in the adaptation of institutional structures can hamper more than supporting transition, knowledge and innovation, although promoted by AKIS stakeholders in many contexts. In a fast-changing digitalised world with

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

the goals of Agenda 2030, countries' institutional structures may lag behind in terms of providing sufficient security and reliable conditions to make well-informed and responsible entrepreneurial decisions. Hence, institutional settings of the past, including various societal values and norms, incumbent governance rules and inherited power structures that may be linked with incrusted constellations of AKIS stakeholders, are sometimes operating as hinderances to transitioning towards a more digital ecosystem approach across European contexts (Charatsari *et al.,* 2023; Kurtsal *et al.,* 2024).

3.4. LEVEL 3. Socio-ecological systems

In CODECS, Elinor Ostrom´s Socio-ecological System (SES) Framework is central to framing and assessing the context in which digitalisation occurs. The use of the framework is important in CODECS because it covers multiple academic fields of sciences, from different backgrounds, and it represents multiple actors, roles and groups, and hence is providing a platform for a common language to compare living labs and **building theory** across them (Ostrom, 2009a). The Ostrom SES framework adopted to the purposes of CODECS builds on institutional analyses and the original SES framework (Ostrom, 2007). It is a multi-level scheme of concepts and variables that have been proven useful for understanding systems in the context of common-pool resources, usually related with natural resources, and has also been applied for other resources, such as digital knowledge (cf. Hess and Ostrom, eds. 2007).

Looking at the literature, it is informed that the rapid digital expansion offers great new opportunities to society, but it also causes severe threats, for instance, in terms of digital divide and risks for deterioration of the natural environment (Melville, 2010). Assessing the literature on digital divide, we encountered five main areas of relevance; 1) access to the digital, 2) education and digital literacy, 3) socio-economic and socio-cultural conditions, 4) community (e-)networks and 5) governance quality (Ciravegna *et al., submitted*). Compared with earlier frameworks linking contexts of technology, organisation and surroundings, this highest level in CODECS would not fit. Instead of using Baker (2012) as a reference, for policy making at national and regional levels, it would be more applicable to deal with societal and natural environments that may risk adverse impacts with new digital developments. Consequences of high inequalities and natural exploitation must from an ethical point of view be dealt with in responsible manners in a market context. As such, policy making can reduce costs and encourage benefits when markets fail to cope with them. Moreover, as stated by the SES, organisations are not limited to firms and institutions and their relationships but include formal and informal norms and values which dominates our minds about what is right and what is wrong, which is the definition of governance (Ostrom, 2011). For instance, the governance context will define whether companies are motivated by employing people in abominable conditions because this is contributing to extended profit margins of the companies, and as a consequence, regulation may be needed to safeguarding minimum living conditions with new developments (IPOL, 2019). The environment at the SES level refers to the physical natural environment as well as regulation services provided in the form of nutrient, water and climate cycles, which are critical to human existence and sometimes taken for given with no value attached to them (Soma, 2006). In CODECS, the idea is to address the potential costs and benefits at such a high generic level, following the understanding of costs and benefits at the lower farm business process level and digital ecosystem level.

Moreover, the Ostrom framework plays an important role in analysing systems because it provides shared concepts and variables that enable comparison between, and gathering of, knowledge across multiple situations, use cases, living labs, etc. On the first level, the framework conceptualises systems into subsystems, including: **resource systems, resource units, governance systems, and actors**. It also includes **interactions**, and **outcomes**, as well as **innovations** (social, technical, organisational, economic, and environmental). These general concepts are then broken down into more specific concepts and variables.

The SES system approach is important when considering digital technologies. This is because **digital ecosystems** can be understood as dynamic systems where digital, social-economic, organisational, knowledge, and physical components converge to support the production, storage, communication, and use of digital technologies and data. With the Ostrom framework, the analysis of digital ecosystems includes, but is not limited to, the role of digital resources (data, application systems, etc.), digital resource systems (platforms, infrastructures, clouds, etc.), digital governance systems (data sharing and use regulation), and actors that are involved in digitalisation.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

The interactions and outcomes of the subsystems are conceptualised in the "**focal action situation" (FAS)** (contained within living labs in CODECS). The FAS exists within a digital ecosystem, which is part of the more extensive SES. These interactions are covering the relations and interactions within and across the subsystems (i.e. governance systems, actors, resource units, and resource systems). Establishing a conducive "digital ecosystem" applicable to the digitalisation of agriculture requires an enabling environment, willingness, and readiness by the actors involved.

To further explore the different subsystem of Ostrom SES, the identification of **resources, capabilities, collaborations, and innovations (RCCIs)** is important. This allows us to not only better understand the context of a living lab within the SES system, but it also allows us to understand how resources and capabilities (individual and collective) operate during transition, to understand when digital solutions can reach to more sustainable agriculture. The RCCIs approach is used to explore Ostrom´s subsystems across the living lab and their FAS. The SES subsystems influence the Digital ecosystems and the RCCIs available to actors involved in sustainable digitalisation of agriculture. For example, a resource subsystem may provide a clear set of standards which allow for interoperability and thus enhancing the digital ecosystem, or a supportive advisory service (actor subsystem) may encourage the capability to innovate, which is central to the RCCIs.

Identification of resources. An acknowledged branch of organisational theory is based on theories defining resources and capabilities, encompassing; 1) a resource-based perspective often held by a firm (Barney 1999), 2) a dynamic capabilities perspective (Teece *et al.,* 1997; Helfat and Peteraf, 2009), 3) a knowledge-based perspective (Kogut and Zander, 1992) and 4) a relational perspective (Dyer and Singh, 1998). Across the different perspectives, definitions of resources are heterogeneous. For the purposes of CODECS, we have chosen the most generally agreed approach defining resources as: 'tangible and intangible goods owned or accessed by an entity (e.g., farm enterprise, living lab, organisation, etc.), which may be utilised in order to create value, achieve an objective, or solve a problem'. An actor´s capabilities concern the ability to deploy resources. While an actor may possess valuable resources, ineffective use or nonexistence of capabilities will prevent full exploitation of such resources. Moreover, an actor´s resources, or access to resources, influence the development and exercise of capabilities.

Identification of capabilities. Capabilities are defined as 'the individual/organisational know-how/abilities to achieve the intended goal', which implies a combination of resources and organisational routines or guidelines. Subcategories of capabilities, such as internal and external, as well as functional and organisational/cultural may be identified. In general, dynamic capabilities can be understood as the ability to reorganise the assets (resources, skills, etc.) that an individual or collective entity possesses not only to be able to respond to changing environments (readiness), but also to increase its capacity for adaptation, survival, and competitiveness (conduciveness).

The RCCIs approach, particularly the dynamic capabilities, contributes to exploring how transitions happen (how RCCIs are utilised to respond to external factors), which makes it relevant to the broader scope of CODECs and its use of the theory of change.

Furthermore, the identification of RCCIs allows the description of the **digital ecosystem conduciveness** and **farmer digital readiness** (across the value chains and the networks associated with the living labs) and the development of digital ecosystem conduciveness indicators. Both digital ecosystem conducive general indicators and context specific indicators will be compared, analysed, and evaluated. For example, living labs or farmers' capabilities and/or resources can be very specific to each farming context, making comparison difficult, also within the SES subsystems. However, if we can classify and identify the resources and capabilities, we will be able to compare conduciveness across digital ecosystems, as well as farmer readiness.

Digital readiness of farmers is understood as the "individual or organisation's ability to adapt and effectively utilise digital technologies and tools in order to achieve their goals and objectives". The farmer digital readiness encompasses a range of skills, knowledge, capabilities, and resources necessary to effectively navigate and leverage digital tools and technologies.

Box 6. CODECS – Identified Resources, Capabilities, Collaborations, Innovations (RCCIs) across Focal Action Situation (FAS) in living labs

In order to address the focal action situations (FAS) across the living labs, a selection of 10 of the 20 living labs was made, including the living labs of Germany, Spain, Czech Republic, Greece, Serbia, Hungary, Latvia, France, Italy, Scotland and Macedonia. Using the Resources, Capabilities, Collaborations and Innovations (RCCIs) approach to investigate, we found the

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

following patterns. First, innovations included technology innovations, market related innovations, environmental and social innovations, interactive innovations, etc. The technology related innovations included to high extents different types of sensors, but also innovative virtual monitoring systems, site specific nitrogen application (spreader), targeted application of chemical spraying to trees, drones, robots and artificial intelligence. Market related included platforms, banners in other webpages, labelling, digital produce markets, apps, product innovations, and intellectual property rights. The environmental social innovations were often stated broadly, but specified into awareness, environmental innovations, and quality of life. Interactive innovations referred to high level of interactivity, but also participatory interactivity, integration between know-how (internal-external), farmer training, collaboration with innovation tech providers, openness towards innovations, processes with user's needs for expression, process optimisation, etc.

The core collaboration partners were generally informed to include companies, cooperatives, producers, private sector, publica administration, research institutes, universities, education and research, professional associations, machine manufacturers, tech providers, community initiatives, customer network, collaborating with farmers, farm network, collaboration in the form of data sharing, problem solvers, media contacts, private advisors, region, state, and relevant stakeholders. Some specific examples included computer scientists for BLOG to communicate problems and how to solve them, network of companies and institutes with which projects have been developed on a national/regional scale (e.g. CNR-IBE) with which commercial relationships are established and national and international relations, advisors and networks, e.g. as the FAO Global Soil Partnership.

Capabilities is about knowledge in the field of agronomy, high level of technical knowledge, attitudes regarding education about innovations, know-how of product production, skills as farmers, learning and collaboration, multidisciplinary, mutual knowledge and complementarity openness and heterogeneity of its members. Moreover, it is about education, experience, expertise, absorption of new information, organisation skills, consumers' digital skills, listening skills of entrepreneurs, scientific knowledge and digital skills and ability to create digital resources. It is also about abilities to expand existing knowledge, deal with topics of general benefit, generate new knowledge, as well as use of data sources generated in a company, and specifically for scientists, abilities to improve models quickly, measure different parameters, system and data integration, optimisation, as well as capabilities to provide feedback, to learn by doing, to offer relevant training, connect teaching and research.

Some capabilities are more technology related, such as capabilities to update relevant technologies, making use of animation, cyber security, decision-making support, dedicated apps, development and customisation of software and forecasting models for digital agriculture, technology testing, whereas other capabilities are more related with choice of business strategy, such as working strategies, management strategies, collaboration, use of online sales channels such as WhatsApp groups, e-mails, web pages, online shops, and ability to attract income from digital means, as well as awareness about new digital technologies and its benefits, monitoring organisation to solve a problem and openness to heterogeneity of members. Furthermore, capabilities can be stakeholder related referring the ability to attracting, mobilising and identify the right stakeholders, building networks, and support stakeholders to meet their needs, and they can be result oriented, referring to capabilities to solve problems, generating new results and perform sustainable operations.

For resources, a large share mentioned by the living labs refer to non-physical assets, such as advisory support, registering support, entrepreneurs' attentiveness, ethics and values, experience, experimental fields, freely available social media, good internet coverage, networks, data storage and processing, testing possibilities, time, and digital agriculture platform. Business related resources included financial resources, capital funding success, infrastructure, investments, agricultural contractors, open source "Open" decision support system, technicians and advisors, whereas physical resources included equipment, forecasting instrumentation, technologies for integration, sensors, actuators, farming technologies for precision fertilisation, irrigation water, land, trial fields, equipment, materials, organisational technologies, RTK GPS system, satellite images provided, weather monitoring stations and delivery services and digital devices. Knowledge related resources included knowledgeable consultants / farm advisors, domain knowledge, physiological knowledge, human resources, technical knowledge (skills), community of practice skills, farmers and technicians willing to participate, organic research and historical valorisation, presence and support from researchers – institutions, and teaching material on agronomy, as well as data, databases, data integration platforms, decision support system, computer forecasting models, new means of large-scale data collection, robust detection AI models and compute power.

3.5. Illustrative examples across the three CODECS levels

In this section, three illustrative examples are provided to assist the understanding how the different conceptual levels can be used to describe the reality, and how real-life phenomena spans across the three layers being distinct although with same or overlapping contact points. The three levels of CODECS follow a system thinking and include the business process level, the digital ecosystem level, and at yet a higher level, we address interlinkages to

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

understand impacts at larger scale by addressing consequences for social, societal and natural environmental circumstances.

Based on the literature review conducted above, the most appropriate components to describe the differences across the levels would be: 1) resources, 2) actors, 3) rules, 4) artifacts, and 5) outcomes. Within each of these levels, these five components have different meanings and are to different extent addressed. To illustrate these interrelated but differences across levels, illustration of two of the 20 living labs of CODECS and their appearance when operating at the different levels are briefly addressed in Table 2, including;

1) Agrifood Technology, Belgium: Ultra-high resolution red-green-blue (RGB) on drones and artificial intelligence (AI) for detection of weeds, diseases and pests in arable crops to minimise the use of plant protection products towards a more sustainable agriculture
2) Farm Management Information System (FMIS), Italy: integration of new and existing databases managed by different actors that related to several parameters such as sheep health, feeding information, quantity and quality of milk production, in order to improving farm management strategies to obtain desired outcome including health monitoring and eventually for future, product traceability.

Table 2 – Examples of how a case can be addressed at different levels

Levels	Agrifood Technology (Belgium)	Farm Management Information System (FMIS) (Italy)
Business processes, level 1	**Resources:** (Experimental) arable fields, human resources, specialised knowledge, financial, natural resources at farm level. **Artifacts:** Ultra-high-resolution red-green-blue (RGB) on drones and artificial intelligence (AI) to detect weed, disease and pest in arable crops. **Actors:** The farmer, his/her family, the advisors, the cooperative, the consortium, agricultural contractors **Rules:** Rules on use of pesticides, data collection rules, technical rules related to production facilitating farmers data collection of data related farm processes. Rules on the use of drones/aerial vehicles **Outcomes:** Efficiency, productivity, better quality of labour, products with less pesticides	**Resources:** Farm-controlled human, infrastructural, natural resources. Farmers' business and social relations. **Artifacts:** Software and hardware of the FMIS; Smartphone/tablet to use the app on field; animal identifier (bolus, microchip etc); Bluetooth gate **Actors:** Sheep farmer, agronomist advisors, vet advisors, dairy processing plant workers, consortium protected denomination of origin (PDO) workers, consumers, other sheep farmers, traders, farm machineries providers, input providers, other dairy processing plants **Rules:** Data collection procedure, rules for dairy sheep system functioning, technical rules related to production facilitating farmers data collection PDO schemes **Outcomes:** Efficiency, productivity, better quality of labour, supply chain coordination
Digital ecosystems, level 2	**Resources:** Expert knowledge, financial resources for innovation, which are needed to reach at a conducive digital ecosystem. **Artifacts:** Digital infrastructure, making use of large amounts of digital data, supported by advanced interconnected clouds, which supports production, compute power, storage, communication, and use of digital technologies and data across networks. **Actors:** Farmers, cooperatives, consortium, extension services, public administration, technology services, agricultural contractors, universities	**Resources:** Knowledge of opportunities to use the FMIS to improve efficiency of the dairy sheep system, basic digital skills of actors in the value chain, IT developers working for the PDO consortium, digitalization of public administration (including animal health services). **Artifacts:** Server/cloud service to store data update of software and hardware of the FMIS computer, open access databases. **Actors:** Technology developers, university research entities, hardware providers **Rules:** Procedure for data management and interoperability, guidelines for using the FMIS.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

	Rules: Data sharing within the farmer network **Outcomes:** Conducive digital ecosystem, the extent to which the enhanced precision technologies minimise the use of chemical plant protection products, as well as the growth and success of the farming, such as the development of new technologies, and the creation of new businesses.	**Outcomes:** Conducive digital ecosystem, improved interoperability among actors databases, FMIS support improved quality of sheep milk production.
Socio-ecological system (SES), level 3	**Resources:** Natural resources, which may be impacted by spraying of crops **Artifacts:** Infrastructure and interlinkages with the natural environment **Actors:** Public administration, cooperatives, consortium, local populations, business in other sectors, consumers **Rules:** Governance of natural resources, support to innovation, local development. (EU regulation on permitted plant protection products) **Outcomes:** sustainability bringing a sensible reduction of pesticides and an improvement of biodiversity. The possibility to improve the image of the farmer in society	**Resources:** Natural outdoor resources at farm level, grass, sheep, land, water, in marginal areas lacking human and financial resources. Innovation policies supporting the development of digital technologies for agriculture CAP supporting the uptake of innovation. Investments by the private sector. Institutional and social capital. **Artifacts:** Infrastructure of IT connection, databases of public administration (e.g. animal health services). **Actors:** Public administration, farmers association, farmers unions, public animal health services, consumers/citizens, banks. **Rules:** CAP rules, social rules (e.g. habits), negative vision of sheep farmers, lack of coordination among actors. **Outcomes:** Coordination in the supply chain, improvement of the reputation of sheep farmers, attraction of young farmers, better natural resource management. Sustainable development by reduced use of water/pesticides, which can benefit natural ecosystems

3.6. Summing up

In order to address the extent to which a system approach can assist in defining costs and benefits, in this chapter it is illustrated how costs and benefits can be generated with a system approach at different levels. While digital technologies are applied at farm level, sustainability outcomes are observed at a multiple level; local, regional, even global. The links between different levels need analytic attention given the multi directions of influence and activities following a system thinking approach. In CODECS, three levels of digitalisation have been identified for the analysis: 1) business processes, 2) digital ecosystems and 3) socio-ecological systems.

The first level is referred to as **business processes.** When digital technologies are introduced into an existing business process, they connect and disconnect the elements of the underlying socio-technical system. Business processes refer to farm related processes as they are, and farm related process as they become after digitisation, i.e. after the introduction of the technology. The performances of digitisation on the farm depend farmer readiness, which depend on the capabilities, motivations, and opportunities at farm level. Farm level **user readiness** can be scaled to involve multiple farms, and this can result in readiness at larger scale, i.e., **system readiness.**

At the second level, a digital ecosystem refers to the digital components of a business ecosystem. It thus can be understood as **dynamic systems where digital, social-economic, organisational, knowledge, and physical components converge to support the production, storage, communication, and use of digital technologies**

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

and data. A digital ecosystem provides the resources necessary to support the digitalisation of processes at farm level: connectivity infrastructures, organisational resources, human resources, knowledge, data, and platforms. A digital ecosystem provides the metarules for the processes. Metarules are 'rules of rules': they are rules that set the principles and the limits for the generation of the specific rules that govern the processes. Moreover, the term digital ecosystem is increasingly associated to the 'economy of platforms'. Given the power of platforms to connect a myriad of users and providers, it is said that a digital ecosystem develops to foster collaboration and complementarity between companies to harness the opportunities emerging from users' demand. In the platform economy, the ecosystem is 'orchestrated' by the platform owner that decides the (meta)rules of access and of operation.

The third level comprises analyses of costs and benefits of digital technologies, which refers to the interaction between processes and natural resources. At this level, the Ostrom framework of socio-ecological systems (SES) is adopted. The original Ostrom´s framework assesses the sustainability of natural resources through the analysis of the drivers that generate pressures on them. On this regard, the framework states that human activities (actor´s subsystem) use **resource units** (assets used by actors in agriculture and rural economies) in their processes. To assess the sustainability of the processes, it is to be considered that resource units are encompassed by **resource systems,** therefore, resource systems are made up of interlinked resource units, including social, economic, technological, and environmental assets. The actors (individual and collective) carry out activities involved inhabit particular contexts, with their own interests, ambitions, capabilities, access to resources, knowledge levels, and beliefs. In turn, activities are regulated by rules and norms generated by **governance systems**. Governance systems can be defined as the rules that establish how decisions are taken. Governance systems are structured through constitutional rules, contractual arrangements, accountability systems, strategic exercises, traditions, and routines. As governance systems define, in the last instance, the distribution of the costs and of the benefits of human processes, they are the dynamic outcomes of power relations between the actors that compose them, and it is not rare that rules generated by governance systems are not coherent with each other.

In the Ostrom terminology, processes are conceptualised as **focal action situations (FAS),** which describe the patterns of interaction between actors, resource units, resource systems and governance systems in specific contexts. The analysis of focal action situations is particularly relevant to cost and benefit assessment, as they allow to analyse the specific weight and role that each component play in specific contexts.

4. Costs and benefits of digital technologies related to sustainability

4.1. Introduction

In order to improve our understanding of how costs and benefits of digital technologies are related to sustainability, we investigate in this chapter what the costs and benefits are, and for whom. Given the multidimensionality of the sustainability concept, it should be no surprise if different individuals or groups have a different perception of costs and benefits of digitalisation. A benefit from our group could be a cost for another. This is why transitions are not so easy. Still, it is important because a better understanding of the meaning of cost and benefit and of their distribution between groups can help to identify appropriate policies. In deepening our understanding, it is important to consider that the impact of the introduction of digital technologies depends on a number of contextual factors. For example, digital irrigation systems can be extremely effective on some varieties and much less effective on other, depending on the sensitivity of the variety to water stresses. The same can be said for the soil, the microclimate, the size of farm, the level of equipment, not to speak of the skills and the experience of different users.

In this chapter, we first address the costs and benefits of from a system perspective, and then focus on the social, economic, and environmental benefits and costs, separately.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

4.2. System outcomes of costs and benefits

The distinction between outputs and outcomes helps to understand how costs and benefits are generated and distributed. Whereas the **outputs** are the direct and tangible results of an activity or process, the outcomes are the changes that occur because of the outputs (Barab, 2014), and depend on how the components of the system are affected by the outputs. Whether system outputs are considered costs or benefits, or whether the costs/benefits are high or low, depend on the **outcomes** they generate for different components of the system, which in other words are the **value** they create. Hence, costs and benefits measure the value that people attributes to the outputs generated by the system (Figure 8).

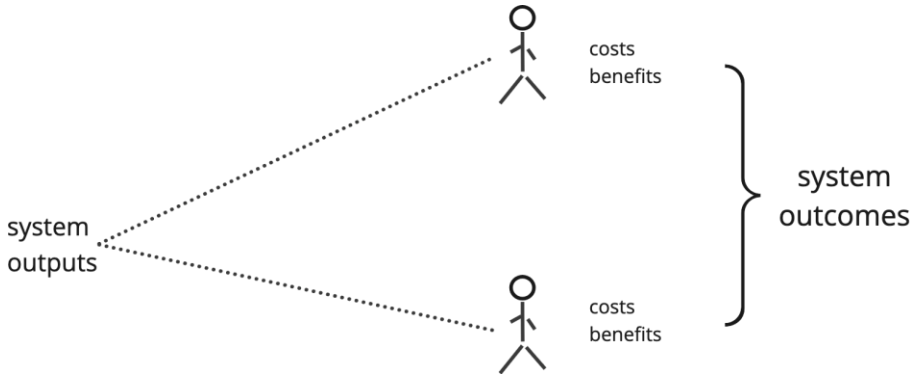


Figure 8 – System outputs and system outcomes

While some actors can benefit, such benefit for some can be a cost for others. For instance, for a farmer, automation can increase the efficiency of operations, reducing the costs and increasing the profitability (Thornton *et al.,* 2017), whereas more automation can imply reduce in needs for human and thus decrease the demand for employees. This will be a cost to the people losing their jobs.

Vulnerable components of a system can be more strongly damaged by pollution levels than non-vulnerable components. The different skills, resources, and motivations of the actors can generate an uneven distribution of the costs and the benefits (McCampbell *et al.,* 2023). This constatation brings us to see costs and benefits as socially constructed; different actors can have different costs and benefits, which can be real or perceived, so that measurement should be considered in relation to a specific actor or group of actors (Rijswijk *et al.,* 2021).

The focus on outcomes helps also to investigate the nature of the costs and benefits of digital technologies. Outcomes, in fact, can have economic, social, and environmental nature. On this regard, the 17 sustainable development goals will be the basis for assessment for CODECS.

Furthermore, this perspective allows us to focus on the process of change across a spectrum ranging from minimal digitalisation to full digital transformation. Integral to this process is decision-making (Emmi *et al.,* 2014), which elaborately shapes the course and extent of change.

For instance, Metta *et al.* (2022) used the socio-technical system approach, advancing from a linear theory driven approach to a system approach to enhance the understanding of how digitalisation can strengthen the digital transformation towards sustainable digitisation, while dealing with complexities and multiple dimensions, and addressing ethical questions. The main entities of the integrated framework include; 1) time-frame, referring to past, present and future, 2) context, referring to the established structural behaviour and trends, 3) system needs, referring to the gap between current and what is desired, 4) system entities (who?), referring to socio, cyber and physical entities, 5) system relationship (how?), referring to way in which entities are connected, 6) system activities (what?), referring to performed operations, tasks, processes, 7) system expectations, referring to normative selection of desired objectives, goals, missions (e.g. the SDGs), and 8) impacts, referring to consequences of mutual interaction between socio-cyber-physical entities.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Decisions concerning change encompass evaluating such diverse activities, gauging potential risks, considering available resources, and estimating possible outcomes:

- Costs may include financial investments, resource allocation, training expenses, and potential risks and disruptions to existing operations.
- Expected benefits, such as increased efficiency, improved productivity, enhanced customer satisfaction, better quality of work, reduced environmental impacts, competitive advantages, or long-term profitability.

Embracing a thorough evaluation approach that transcends traditional financial parameters is gaining momentum in significance, especially in a landscape marked by **complex socio-technical and ecological challenges**, ranging from optimising resource utilisation and effective crop management to elevating productivity or enhancing farmers' quality of life. These challenges encompass a spectrum of concerns, including data privacy, cybersecurity, technological disparities, and ethical issues (Mondejar *et al.,* 2021). This growing complexity holds relevance within both scientific and policy spheres, and scholars' experiences underscore that tackling these multifaceted problems requires more than isolated disciplinary methods.

In our conceptual framework, we adopt an interdisciplinary approach, acknowledging the interplay between social, cyber and physical (artifactual and ecological) systems. Developing such a holistic information system requires considering the business, user, and technology context, along with other strategic, softer, political, and social factors. Effective decision-making at different scales (business process, digital ecosystem, socio-ecological systems) necessitates a comprehensive understanding of the interplay between change, decision-making, and costs and benefits.

Hence, there is a mismatch of defining costs and benefits if costs are seen from the "perspective" of the entity incurring expenses, while benefits can be perceived from multiple stakeholder perspectives, including customers, employees, society, and the environment. Additionally, documented costs are often noted as immediate and tangible, while benefits are judged to be long-term and intangible, leading to a divergence between perceived costs and benefits. For instance, if costs are judged long term (e.g. climate change), whereas social costs (i.e. employment) are judged short term, there is a mismatch and difficulty to compare. (i.e. different "timeframe"). Furthermore, costs are relatively easier to measure and quantify, whereas quantifying and valuing benefits can be more challenging (e.g. increased innovation or ethical values), leading to discrepancies in the assessment. Besides, different stakeholders may "prioritise" costs and benefits differently based on their interests and objectives, and it is not straight forward to make trade-offs between commodities in a market and e.g. biodiversity, because comparisons are made between resource units and system units.

From a theoretical perspective, this leads us to the issue of incommensurable values, which makes monetary valuation complicated (Munda, 2004; Soma, 2006; 2010). Incommensurable values are defined as: 'the absence of a common unit of measurement across plural values, entails the rejection not just of monetary reductionism but also any physical reductionism' (Martinez-Alier *et al.,* 1998 p 280). Further, a distinction has been made between 'social incommensurability', referring to the existence of a multiplicity of legitimate values in society, and 'technical incommensurability' which stems from the multidimensional nature of complexity and refers to the issue of representing complexities in descriptive models (Munda, 2004). This implies that when values are commensurable, the benefit of a monetary valuation system is more reliable because it is fully clear what the 'trade-off' values are, and when valuing incommensurable values, qualitative descriptive impact assessments can more clearly give a true picture of what is evaluated against what (Ramos *et al.,* 2015; Soma *et al.,* 2014). In CODECS both quantitative and qualitative impact assessments are conducted for these reasons.

The scientific literature offers diverse perspectives and methodologies to understand costs and benefits in digitalisation. Approaches range from IT investment evaluation to the economics of information technology, digital transformation and innovation, organisational change and management, and social and ethical implications. These studies examine the impact of digital technologies on productivity, innovation, market competition, economic growth, business models, customer experiences, operational processes, employee training, change management, privacy, data security, equity, and societal impacts.

Traditional appraisal techniques encompass conventional economic, strategic, and analytical approaches. These methods have been supplemented with techniques designed to account for elusive indirect costs that are becoming

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

more prevalent in digitalisation processes or by sympathetic techniques that ensure that the evaluation is appropriate, effective, and able to capture the relevant aspects and potential impacts of digitalisation.

However, current research falls short in providing an integrative and interdisciplinary approach to comprehending the trade-offs, risks, challenges, and factors that contribute to the full range of costs and benefits in digitalisation. In addition, this gap hinders our understanding of the complexities and dynamics involved in the relationship between costs and benefits. To address this limitation, we propose through our conceptual framework an integrated approach, that considers a broad spectrum of interconnected factors, encompassing technical, technological, social, cultural, economic, financial, environmental, and political aspects. Such an approach will enable a thorough assessment of the benefits and costs of digitalisation at various levels and for various actors, providing a more comprehensive understanding of their implications**. A special focus on the cost and benefits** will be given to the farmer's perspectives, as they are the users of the technologies and have documented cost and benefits that can assist in making decisions to get digitalised.

4.3. Social benefits and costs

In this section, we investigate the social benefits and cost of digitalisation within the framework of interest of CODECS. Digitalisation could have the potential to substantially enhance various facets of social, economic and environmental human domain. This encompasses improvements in overall well-being, a healthier labour environment, heightened knowledge transfer and innovation, increased resilience under adverse conditions, and expanded socioeconomic opportunities. However, it is imperative to acknowledge that benefits and costs are not uniformly or equally distributed across social groups. The variability in outcomes is attributable to a multitude of factors, including differential access to digital technologies, individual skill levels, supportive policy frameworks, and market dynamics. Addressing these disparities is crucial to ensure a more equitable distribution of its benefits and costs.

Social benefits and costs have a lot of different dimensions in the literature and have been reviewed throughout this document. For instance, Mondejar *et al.,* (2021) address social positive benefits of digitalisation, referring to improvements of healthcare and equal access to health, and use of IoT, which increased especially during the COVID-19 pandemic as an efficient alternative to access health services while respecting social distancing measures. Moreover, consumers have benefitted from telemedicine, bringing solutions to consumers regardless of their location and income. Besides the promotion of digital tools for wellbeing and improving quality of life through facilitating access to health care, they also refer to challenges of equal data access, digital poverty, increased inequality and cyber security. Rolandi *et al.,* (2021) categorise the social impacts and link them to potential outcomes, including; 1) individual impacts with outcomes on health, learning, responsibility, skills, well-being, 2) access impacts, with outcomes on ICT, resources, 3) rights impacts, with outcomes on autonomy, equity, gender gap, power, resilience, 4) social capital impacts, with outcomes on cohesion, identity, inclusion, participation, trust, and 5) control impacts, with outcomes on prediction, privacy, security, surveillance, transparency and responsibility. In the system thinking literature referred to above, distributional/equity issues have been addressed by Erickson (2008), while the literature on socio-cyber-physical interactions refer to responsibilities in particular as a core social mechanism, while 'socio' as such refers to the coverage of actors, groups, communities and institutions (Rijswijk *et al.,* 2021; Maye *et al.,* 2019). Belafoutis et al. (2020) linked social aspects to farm level labour conditions such as time, stress, heavy labour, workers illness and accident. For Vourikari *et al.,* (2022), social aspects include communication, collaboration, safety and problem solving, whereas Barner *et al.,* (2019) refer to social characteristics, which in analyses refer to variables like education, age, etc. AKIS identified a series of actor categories and put the farmer at the centre of the debate, including input suppliers, consumers, banks and extension services (see Figure 6). Within this literature, social aspects are referred to more in the form of co-operation, co-innovation and cross border collaboration (Moreddu and Poppe, 2013), and they also refer to competition, education and acceptance, which also are considered relevant social factors at macro level. For AKIS, social factors include co-construction and co-learning, (Sutherland *et al.,* 2023), as well as norms and values (Coquil *et al.,* 2018). In the ecosystem perspectives, the social dimensions are referred to as; diversity, employment, trust and regulatory issues (Jacopides *et al.,* 2019), as well as co-evolution. Furthermore, users readiness have been linked to **internal drivers**, which refers to physical and psychological capabilities, physical and social opportunities and reflective and automatic motivation (COM) (McCampbell *et al.,* 2023).

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

In a system approach, societal benefits are often referred to as wellbeing. This brings us to the literature of Sen (1985; 1999), who challenged the theories of utility and resource maximisation, arguing that the concept of capabilities must be seen superior, referring to among others, quality of life instead of purely economic growth, because it is important to account of wellbeing of deprived people. CODECS acknowledges this important contribution of capabilities to emphasising the system values, however, it is also emphasised that when using the capability approach in this deliverable, it is also taking into account some of the criticism to this work, including that it is too general and lack specificity about guiding which capabilities are most central to a society, and what minimum level of what capabilities can ensure social justice (Nussbaum, 2007).

The introduction of any innovation can generate social divides between ‘winners’ and ‘losers’, which can be related to specific variables. The literature identified in ‘age, gender, education, income and geography’ the main factors creating inequalities in digitalisation. The concept of the 'grey divide' highlights the differences between digital natives, individuals born in the era when digital devices and connectivity were already widespread, and 'digital refugees', i.e. individuals who have had to adapt to this circumstance, such as older people who often need external support (Lolich *et al.,* 2022; Tirado-Morueta *et al.,* 2021). Gender-related digital inequalities persist at global level, with women facing barriers and stereotypes that limit their access to education and employment opportunities in ITC sector (Perifanou and Economides, 2020; Macaya *et al.,* 2021). Education plays a significant role in digitalisation, it has been observed that higher levels of education facilitate ICT adoption (Cruz-Jesus *et al.,* 2016). Income levels are correlated with the acquisition of digital skills, in particular access to connectivity, infrastructure facilities and access to digital devices, especially in developing countries. (World Economic Forum, 2016; Elena-Bucea *et al.,* 2021). Finally, also geographical position affects digital inclusivity, marginalised or rural areas can face challenges such as lack of infrastructure and high connectivity costs, which require customised solutions (McMahon and Akçayır, 2022).

Generally speaking, key situations can be highlighted where inequalities in digitalisation are at the expense of social cost to individuals, especially in the most vulnerable groups. First, access to digital, which occurs in fundamental daily services such as health care, financial services, public administration, and education, can become inaccessible to certain categories of individuals (Adhikari *et al.,* 2021; Ranchordás, 2022). This accelerated during the COVID-19 pandemic in which several of these services moved online caused several disruptions (Vasile *et al.,* 2021 and Aissaoui, 2022). Second, digital literacy concerns the need to increase knowledge and awareness of information technology using it as a tool to bridge the digital divide (Silva *et al.,* 2022). This can happen through educational programmes with broader scope than just schools (Adhikari *et al.,* 2021). Third, the socio-economic and socio-cultural conditions can determine social inclusion and improved quality of life (Pinto *et al.,* 2022). This includes structural issues such as the gender gap, geographical disparities and economic development opportunities (Perifanou and Economides, 2020; Szeles and Simionescu, 2020). Fourth, digitisation at the service of the community focuses on equal connectivity and creation of supportive digital and social networks (Riddlesden and Singleton, 2014). Fifth, the category of the quality e-government, that highlights the challenges in the use of technology in the governmental context, have an impact on citizens and policy makers who must address these developments while avoiding further inequalities (Pariso and Marino, 2020).

Moreover, certain groups of individuals are more affected by the social costs of digitisation than others, including elderly people marginalised or rural communities, workers, students, women, and people with disabilities are facing different challenges in accessing and benefiting from digitisation. Much attention in the literature is given to the category of citizens as users of digital services offered by the public system and their experience with these inevitable developments in urban system (Caragliu and Del Bo, 2022, Spada *et al.,* 2015).

Farmers, a group of actors of high interest to CODECS, do not always have access to effective training and support resources that support the adoption of technologies in agriculture (Giua *et al.,* 2022; Hennessy *et al.,* 2016; Martens and Zscheischler, 2022). Because they often are left on the side-lines of technology development, they are unable to benefits from digital tools. This imbalance can lead to division in the sector, with tech-savvy farmers taking advantage of technological benefits and increasing their productivity by improving efficiency, and others lacking access to these innovations and struggling to compete. Inequalities in learning opportunities could exacerbate existing rural-urban divides, as remote farmers may face challenges in accessing quality training programmes. These discrepancies may impede overall agriculture sector growth and resilience, with the potential to perpetuate socioeconomic disparities of the workers.

Funded by the European Union

CODECS has received funding from the European Union’s Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

The existing literature on digital agriculture has identified potential social impacts of digital technologies at various general levels, including rights (e.g., resilience), access (e.g., resources), and individuals (e.g., health and skills) within the agricultural sector (Rolandi *et al.,* 2021). Rose *et al.* (2021) highlights the involvement of people at all levels of social impacts and encourages research to focus on evaluating social aspects related to humans engaged at the farm level to avoid create more social issues than the technologies may solve (*ibid.).* These human impacts are also referred to as intangible costs and benefits related to the use of digital technologies (Murphy and Simon, 2002). Due to their complex nature, assessing these aspects poses challenges. It is essential to recognise that digital technologies should not be considered universal, as their impact is also shaped by socio-economic, cultural, and political factors within different contexts (Klerkx and Rose, 2020). This complexity makes studying the social aspects of digital technology usage challenging. By understanding how digital technologies influence people and their farming activities, we can share valuable knowledge with other farmers and understand and diminish resistance to new technologies. Policymakers can leverage these insights to design and support policies that mitigate any adverse social effects resulting from the use of digital technologies at the farm level.

Equitable access to digital resources, effective training, supportive policies, and collaboration are crucial for technology adoption and bridging the digital divide. Inclusive practices, considering gender dynamics and accessibility for marginalised groups, are key. Aligning with market demands, ensuring safety, and measuring tangible improvements in health and satisfaction are vital. Adaptability to new technologies and digital literacy significantly influence the extent of benefits, especially in agriculture and rural socioeconomic empowerment. Often the social divide is not sufficient to describe the impact that digital technologies can have. As one function of digital technologies is to connect people, things, and machines to perform new functions, one of the outcomes observed is the disconnection of existing social relations consequent to digital technologies. Moreover, given that the key to digitalisation is data, the regulatory gap in relation to collection and use of data is one of the most important sources of social impact. Finally, the advent of artificial intelligence has generated concerns that go much beyond the social divides. Several organisations have started to elaborate on potential risks related to digital technologies, and European legislative bodies have accelerated a process of regulatory development to address the emerging risks. The recent document of the UN AI advisory body (2023) has listed the potential risks generated by AI (Table 3).

Table 3 – Risks related to AI (Source: UN AI advisory body, 2023)

Individuals	**Groups**
Human dignity/value/agency (manipulation, deception, nudging, sentencing)	Discrimination/unfair treatment of sub-groups, including on basis of gender
Life, safety, security (autonomous weapons, autonomous cars, interaction with chemical, biological, radiological and nuclear defence)	Group isolation/marginalisation
Physical and mental integrity, health and safety (diagnostics, nudging, neurotechnology)	Functioning of a community
(other) Human rights/civil liberties, e.g. fair trial (recidivism prediction), presumption of innocence (predictive policing), freedom of expression (nudging), privacy (biometric recognition)	Social equality/equity (unfair treatment of groups, including on basis of gender)
Life opportunities (education, jobs, financial stability)	Children, elderly, people with disabilities
Society	**Economy**
International and national security (autonomous weapons/disinformation)	Power concentration

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Individuals	Groups
Democracy (elections, trust)	Technological dependency
Information Integrity (mis- or disinformation, deep fakes, personalised news)	Unequal economic opportunity
Rule of Law (functioning of and trust in institutions, judiciary)	Resource distribution/allocation
Security (military and policing uses)	Under-/overuse of AI, techno-solutionism
Cultural diversity and shifts in human relationships (homogeneity, fake friends)	
Social cohesion (filter bubbles, declining trust in news, information)	
(Eco)systems	**Values and Norms**
Stability of financial systems	Ethical values
Risk to critical infrastructure	Moral values
Strain on environment/climate/natural resources	Social values
	Cultural values
	Legal norms

4.4. Economic benefits and costs

The literature often emphasise that some of the main drivers, barriers as well as impacts associated with the introduction of digital technologies in a system, are economic. Ferrari *et al.* (2022) find that high costs of digital technologies and modernisation of the farm infrastructure, together with lack of funding hinder digitalisation in rural areas are influential. They also discover that economic drivers related with market demands, organizational structures, and business needs like optimisation, access to finance and labour, affect the adoption of digital technologies. Among the potential impacts of digitalisation, Ferrari *et al.* (*ibid.*) further identify socio-economic impacts related to labour, financial and management aspects as well as market models, which may be positive, as well be negative, especially, for small business owners.

Different categories of literature address economic benefits and costs with digitalisation. For instance, Niehof (2022) refers to a risk of a one-sided sustainability approach with focus on business only, centred around customers' demand, faster and more efficient performances, and the understanding of digitalisation as business as usual. Mondejaar *et al.,* (2021) held a broader perspective, referring to economic factors such as strengthening of productivity, services and livelihood worldwide. Rolandi *et al.* (2021) distinguished between economic impact areas and outcomes, with; 1) organisation as area of impact, linked the following outcomes; autonomy, cooperation, financial risk, incomes, marketing, product/process security, productivity, resilience, resource efficiency, responsibility, transaction costs, 2) value chain as the impact areas, linked with the following outcomes; bargaining power, food quality, resource efficiency, transparency and trust, and 3) market as impact area, linked with the following outcomes; equal opportunities, market concentration, prices, stability and transparency. Balafoutis *et al.*

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

(2020) listed the following economic factors for business processes; productivity, quality of product, revenue, input costs, variable costs, crop wastage, and energy use.

In a system perspective, economic costs and benefits pertain to the direct and indirect financial impacts that the process of change has on the involved parties and among the system components. Costs involve expenditures for technology acquisition, infrastructure upgrades, training, and potential disruptions to existing operations. These costs also encompass implicit factors like opportunity costs related to reallocating resources towards digital initiatives, data management, technological risks, administration control, security and protection costs, data governance and privacy, coordination, and collaboration costs. Appendix 2, Table A2.1, introduces a theoretical distinction encompassing operational, investment, transition, switching, transaction, and risk Management costs. A brief explanation of different types of costs are provided in the following.

- Operating Expenses (OPEX) encompass the ongoing costs required for the day-to-day functioning of the digital system. This category typically includes things like salaries (excluding those related to training and development), utilities, rent, and routine maintenance. Other costs can be associated with keeping equipment, systems, facilitating good working condition, supporting services, assisting with technical issues, maintaining systems or customer service, updating and improving existing hardware and software systems to enhance functionality, security, or efficiency, as well as regular use printer ink, electricity, cloud services, water and gas that fluctuate with consumption, and disposal of waste materials and outdated equipment, etc.
- Capital Expenditures (CAPEX) involve the investments made to acquire, upgrade, and maintain digital and physical assets that support the adoption and integration of digital systems and technologies in farming operations. Typical capital expenditures such as ‘internet access’ are incurred by individuals or businesses to connect to the internet, enabling them to access online resources, communicate, and utilise various digital services. Other investments can be associated with servers, data storage, advanced computing resources necessary for processing and analysing agricultural data, high-tech equipment such as drones, autonomous tractors, sensors, and other precision agriculture tools, as well as management software, crop modelling applications, and decision support systems, that help in optimising farm operations and resource use, and communication networks, etc. By focusing on digital assets and systems, CAPEX is distinguished from Operating Expenses (OPEX) in that it is capitalised and depreciated or amortised over the useful life of the asset, reflecting its long-term benefit to the company.
- Business process related transition costs refer to the expenses associated with adapting or shifting from one state of system to another, often involving restructuring or reorganisation expenses to enhance efficiency, productivity, and data-driven decision-making. Key components of these costs include expenses for educating farm staff and management in new digital technologies, tools, and methodologies, indirect costs on time spent by employees in training and upskilling sessions, costs involved in rethinking and redesigning farming operations and processes, expenses related to tailoring digital agricultural systems, software, and tools to meet the specific needs and conditions of a particular farming operation, as well as cost to aligning data formats, protocols, and procedures to ensure seamless integration and interoperability of digital systems across different devices, platforms, and operations within the agricultural sector, etc. Transition costs are crucial investments for modernising agriculture through digitalisation, to overcome initial barriers and set the foundation for long-term gains in sustainability, efficiency, and productivity.
- Switching costs is a sub-typology of business-related transition costs that refers to the expenses and challenges associated with moving from an existing system or technology to a new one. Switching costs represent the barriers that businesses or organisations face when changing technologies or systems, which can be a significant consideration in the decision-making process regarding whether to adopt new digital solutions. Resistance to transition can be manifested as an elevated switching cost that must be incurred.
- Transaction costs pertain to the expenses incurred during the exchange of goods or services,

Funded by the European Union

CODECS has received funding from the European Union’s Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

encompassing elements such as negotiation, enforcement, and contracting. It includes investments in anti-virus software, firewalls, and other cybersecurity technologies to safeguard computer systems, networks, and data from potential threats such as malware, viruses, and unauthorised access. Additionally, the cost includes measures taken to ensure the physical security of the organisation's facilities, including access control systems, surveillance cameras, and security personnel. These measures are designed to prevent unauthorised access to sensitive areas and protect against theft, vandalism, and other physical threats. Transaction costs in digital contexts are multifaceted and extend beyond mere financial expenditures, encompassing ethical, legal, and social considerations that are crucial for sustainable and equitable digital systems.

- Risk management costs refer to the financial investments and efforts dedicated to identifying, assessing, and mitigating various risks that can impact the development, implementation, and operation of projects or systems, especially in technology-driven environments. These costs are integral to ensuring that potential challenges and threats are effectively managed to minimise their impact on project outcomes and organisational objectives. Key areas of risk management costs are invested during development phase of a project or system, during the rollout or implementation of a project or technology, and with the use of new or existing technologies within an organisation. This includes investments in cybersecurity measures to protect against threats such as data breaches and cyber-attacks, regular updates, and maintenance of technological systems to prevent obsolescence and conducting technology assessments to ensure compatibility and scalability. It also involves monitoring emerging technological trends and regulatory changes that could impact the organisation's technological infrastructure. Risk management costs are crucial for proactive planning and response strategies, helping organisations navigate uncertainties and protect their assets, reputation, and operational continuity in a rapidly evolving technological landscape.

Furthermore, economic benefits of digital transformation include increased (data-driven) efficiency, improved quality, and productivity, selling price, enhanced market access and information, customer satisfaction, and new revenue streams (Appendix 2, Table A2.2).

- Operational Efficiency benefits refer to the advantages gained through the implementation of digital technologies and data-driven approaches, leading to streamlined and improved agricultural processes and higher productivity and resource utilisation, higher yields and output, lower operational expenses by optimising resource usage, reducing waste, and improving overall cost-effectiveness, efficient management of logistics and supply chains, minimising delays and improving the flow of agricultural products, and enhanced handling, storage, and processing of agricultural products after harvesting, reducing losses and ensuring product quality, among others. These benefits collectively contribute to the overall operational efficiency of agricultural practices, resulting in better resource management, increased profitability, and more sustainable agriculture.
- Enhanced Decision-Making benefits include making informed decisions about sales strategies and customer engagement, including utilising data to tailor product offerings, pricing, and marketing efforts to meet customer needs and preferences effectively, and data-driven insights to optimise agricultural processes and resource allocation. Data-based decisions will enhance the efficiency of planting, harvesting, irrigation, and other agricultural operations, leading to improved resource utilisation and cost-effectiveness, etc. This involves data cleansing, validation, and integration to maximise the value of data for decision-making and agricultural operations.
- Business and Economic Growth benefits encompass a) increased market share, improved revenue streams, and a stronger position in the agricultural industry, contributing to overall business and economic growth.
- Economic Growth and Livelihood Enhancement benefits include implementing pricing strategies based on real-time data, and securing better prices for agricultural products, enhancing agricultural productivity,

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

improving product quality, and ultimately resulting in increased revenue for farmers, developing Short Food Supply Chains (SFSC) that can lead to increased revenues for farmers, as these chains often prioritise fair pricing and sustainability as well as opening up avenues for farmers to access funding opportunities, grants, and loans, which can further support economic growth and livelihood enhancement in the agricultural sector.

- With Financial Well-being Enhancement benefits digitalisation helps farmers mitigate losses and optimise their operations, ensuring a more stable and consistent income. By reducing risks and improving resource management, digital tools contribute to the preservation of farmers' financial stability. Furthermore, digitalisation provides farmers with access to valuable data and insights, enabling them to identify new opportunities for revenue generation. This may include diversifying crops, adopting more efficient practices, or participating in value-added agricultural activities. As a result, farmers can maximise their income potential and overall financial well-being.
- Enhanced Food Standards benefits primarily focus on improving product quality and include; enabling farmers to monitor and manage various aspects of their agricultural practices with precision. This results in better control over factors such as irrigation, pest management, and soil nutrition. Consequently, the quality of agricultural produce, including crops and livestock, is significantly enhanced. This improvement in product quality ensures that consumers receive safer, healthier, and more consistent food products. Digital tools also facilitate traceability and transparency throughout the supply chain, making it easier to identify and address any issues related to food safety and quality. This not only benefits consumers but also enhances the reputation and marketability of agricultural products, ultimately contributing to safer and higher-quality food standards.
- Trade and Market Development benefits include digitalisation when empowering farmers and stakeholders with improved access to markets and valuable market information. Through digital platforms and marketplaces, farmers can connect directly with buyers, eliminating intermediaries and expanding their market reach. Additionally, real-time market data, price trends, and demand forecasts are readily available, enabling informed decision-making. This enhanced access to markets and information enables farmers to sell their products at competitive prices and optimise their sales strategies. Also, it includes digitalisation when facilitating the integration of agricultural markets on a global scale. Farmers can explore international markets, access buyers from around the world, and participate in global trade networks. Digital platforms and e-commerce solutions enable cross-border trade, export opportunities, and collaborations with international partners. This global market integration enhances the competitiveness of agricultural products in the global marketplace, opening new avenues for growth and trade expansion.
- Innovation and Collaboration benefits encompass creation of innovative digital ecosystems within the agricultural sector. These ecosystems comprise a network of farmers, agribusinesses, technology providers, researchers, and government agencies collaborating to develop and implement cutting-edge solutions. Through digital platforms, data sharing, and collaborative initiatives, stakeholders work together to address agricultural challenges, drive innovation, and create sustainable practices. These ecosystems become hubs for experimenting with emerging technologies such as IoT, AI, and blockchain to enhance agricultural processes, increase productivity, and promote environmental sustainability. The synergy of diverse expertise and resources within these ecosystems accelerates the pace of innovation, resulting in novel solutions that benefit the entire agricultural industry.

Just as with social costs and benefits, it is useful on the economic front to understand the distribution of costs relative to benefits, the critical factors, as well as the impacts in the short and medium-to-long term. Uneven distribution of ‘upgrade costs’ and infrastructure modifications can lead to financial stress for farmers, particularly small-scale ones, impacting profitability and economic stability. Disproportionate expenses create technological disparities, hindering competitiveness and innovation. High costs limit access to innovative technologies, hampering productivity efforts. Operational inefficiencies arise for those unable to afford upgrades, impacting productivity. Market competitiveness

Funded by the European Union

CODECS has received funding from the European Union’s Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

and sustainability suffer due to irregular cost distribution, and innovation and resilience are hampered. Unequal expenses exacerbate rural-urban disparities, constraining modernisation and hindering rural development.

In CODECS the main level of analyses of economic costs and benefits takes place at the farm business level, since digitalisation commonly generates changes on the farm (Munz, 2024). Furthermore, the farmer/user of the technology is the one making the decision of adoption of the technology or not. For the economic analysis, comparisons of "with" and "without" the digital technology alternatives will be carried out. This will allow the estimation of the net benefits deriving from the adoption of digital technology and will provide insights on whether the adopted digital technology is a viable alternative to the existing technology (Gangwar *et al.,* 2022; Bucci *et al.,* 2020; Mutenje *et al.,* 2019; Mburu *et al.,* 2007). The assessment of economic performance takes into account capital expenditures (investment costs) and transition costs related to the adoption of the digital technology as well as farm operating expenses i.e., annual production costs. Scenario analyses and/or stochastic analyses as well as sensitivity analyses will be utilised (Munz and Scheule, 2022; Mutenje *et al.,* 2019) to consider economic risk and uncertainty and to identify necessary conditions for feasible digitalisation solutions (Mburu *et al.,* 2007) as well as regulatory/institutional drivers of adoption e.g., economic incentives (Ferrari *et al.,* 2022). Throughout this report the economic costs and benefits have been addressed according to relevant literature in multiple manners.

The analysis of the costs of digitalisation should consider the time necessary for the mutual adaptation between the technology and the socio-technical network in which it is introduced. For this reason, we need to identify at least three phases of farm digitalisation, each of which entails a different mix of costs: a) setup; b) transition; c) full operation.

- Setup Stage: This initial phase involves the upfront investments required to start the digitalisation process. Costs include purchasing hardware, software, and other infrastructural components, as well as initial training and development efforts. An example might be investing in sensors and data analytics platforms for precision farming.
- Transition Stage: After setup, the transition phase focuses on integrating and optimising the new digital tools within existing processes. Costs here relate to further training, system integration, fine-tuning of technologies, and possibly scaling up solutions. This stage might involve adjusting farming practices to fully utilise data from new sensors, or even including data harmonisation processes.
- Full-operation Stage: The final phase is characterised by the ongoing operation and maintenance of the implemented digital solutions. Costs include regular updates, technical support, and continuous training for new features or technologies. Over time, it may also involve gradual upgrades or replacements of technology. An example could include regular software updates for farm management systems.

The mix of costs changes along the shift of the farm from one phase to another. As the introduction of a technology (in the form of goods or services) can have a duration of several years, the analysis of the return on investments should consider all the costs sustained in the three phases. In Figure 4, the economic terms used throughout this deliverable has been categorised into a total of six categories.

Table 4 – Terms used in this document categorised, although nonexclusively, according to possible scales of economic performance (i.e. efficiency, effectiveness, transparency, credibility, accountability/legitimacy and inclusiveness)

Efficiency related	Effectiveness related
Economic growth, productivity	Economic areas (value-chain, organisation, market)
Economic profitability	Socio-economic effects
Financial aspects	Economic domain, discipline
Economic resources	Economic innovation

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Transparency related	Accountability/legitimacy related
Economic dimensions	Economic stability
Socio-economic system	Economic performance
Socio-economic characteristics, factors, components	Socio-economic disputes
Economic paradigm, discipline, approach	
Inclusiveness related	**Credibility related**
Economic development	Economic sustainability
Distribution of costs	Socio-economic life
Socio-economic governance	Socio-economic drivers
Socio-economic empowerment	Economic development
Economic disparities	

4.5. Environmental benefits and costs

A natural ecosystem involves complex interlinkages of physical components and cycles which are interrelated, creating the needed conditions for biological factors and life (Ackoff, 1971). Although the complexities of a natural ecosystem are extremely high, it is possible to link the system thinking itself to information systems thinking because, among others, this can mediate or moderate rebound effects by changing data and information availability (Melville, 2010). Whereas economic and social costs and benefits of digitalisation directly impact groups of actors, environmental costs and benefits impact people via a double mechanism: first the environment is impacted, in various dimensions (e.g. climate change and eutrophication), through biochemical mechanisms, and second, costs and benefits are assessed through a system of values which depend on the group of actors. It is necessary to consider these two mechanisms.

The United Nations Sustainable Development Goals intend to improve human well-being and promote conservation of ecosystems, urging for the needs for understanding complex interrelationships between social and natural systems as well as complexities of ecosystem services (UN, 2015). Ecosystem services have urgently been addressed as a means to bridge between the natural and the human world. As such, economic and social costs and benefits of digitalisation directly impact groups of actors, and environmental costs and benefits impact people via the double mechanism.

Value-systems can be understood as intra-psychic constellations of norms and perceptions that guide human judgement and action (Costanza, 2020). Extensive research efforts have been conducted since the early 1970s to value natural capital and ecosystem services (including Bennet, 1984; Costanza *et al.,* 1997; Hein *et al.,* 2006; Barbier *et al.,* 2011; Grabowski *et al.,* 2012; de Groot *et al.,* 2012; Kim *et al.,* 2015; Pendleton *et al.,* 2016). The definition of ecosystem services stems from some years back; 'the benefits people obtain from ecosystems' (MEA, 2005) but has been nuanced in more recent years to reflect on complexities. For instance, the Economics of Ecosystems and Biodiversity (TEEB), applied an "'Ecological and Economic Foundations' approach explaining ecosystem services as 'useful things' ecosystems 'do' for people, directly and indirectly whereby it should be realised that properties of ecological systems that people regard as 'useful' may change over time even if the ecological

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

system itself remains in a relatively constant state(De Groot *et al.,* 2010). The most common reasoning in the literature about valuation is based on individuals having a multitude of values to assign to various ecosystem services available from the marine environment to influence their welfare. For example, an individual can enjoy consuming seafood resulting from provisional services from the marine environment (i.e. a consumptive direct-use value), as well as spiritual mediation by the beach (a non-consumptive direct-use value) and would like to pass on these uses to his/her future children (non-use bequest value). An overview of types of values in the literature is displayed in Figure 9.

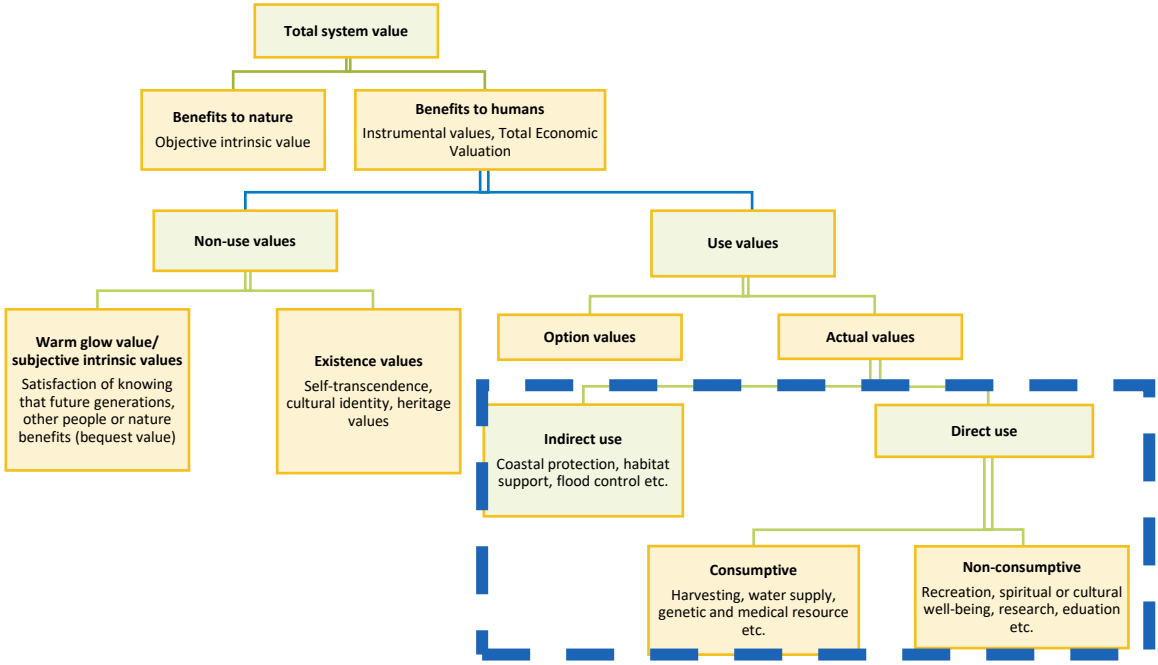


Figure 9 – Typology of values, adapted from Sandler (2012), Davidson (2013), Turner (2010) and Barbier et al. (2011)

The overview of ecosystem values provided in Figure 9 distinguishes at a higher level between 'benefits to nature' and 'benefits to humans'. The 'benefits to nature' category refers to objective intrinsic values, meaning that the values have an end in itself, i.e. inherent worth, which can relate with historical development and evolution, implying they are not instrumental, not human based, and thus independent from human acknowledgement, knowledge, design, etc. In other words, the objective intrinsic values are non-conditional (Sandler *et al.,* 2012). For instance, non-discovered species are in this category highly valuable according to the objective intrinsic value category.

Intrinsic value may also refer to subjective intrinsic value, implying that the value has a human reference, and thus is conditional (Sandler *et al.,* 2012). For instance, when new species are discovered by humans who give them a subjective value as end in itself, with no instrumental value attached, this value gives a 'warm glow'. The benefits to humans, i.e., the instrumental values get a lot of interest in the literature and belong to the category that is included in most valuation surveys. This category is distinguished into two values: the 'non-use values' and the 'use values'. The non-use values are based on feelings of 'warm glow' and existence, are very hard to capture in monetary values, basically because our feelings do not directly belong in a market transaction setting. To put a monetary value on feelings could even distract from the actual value of the feeling (Soma, 2006).

The 'use values' are further specified into 'option values' and 'actual values'. The 'option values' include leisure, commercial, industrial, agricultural, pharmaceutical applications, and water-based developments. From this perspective, values potentially change over time to maintain a pool of species and genetic resources for future potential uses, for which some may not be known now (Emerton, 2009). Note that a lot of uncertainties are associated with the 'option values' given that they change over time, and as such overlap with what we do not know, namely the 'intrinsic value' category. Similarly, because humans may not know the exact properties and how they change, monetary valuation gets complicated, risking biases in valuation.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

The actual values are further distinguished into 'indirect use' and 'direct use'. 'Willingness to pay' to value these two categories are often used in valuation methods to account for these values. Notably, the 'indirect use' includes exploitation of regulation services, which may not be fully understood by people, and even if they are understood, people may not consider it relevant to pay for them with their limited budget. Moreover, one service can have multiple values to a single person (e.g. direct consumption, option and intrinsic values), which may not be captured by a simple 'Willingness to pay' because they are incommensurable to a plain market value (Soma, 2006).

To avoid these complicated matters, the existing valuation methods and defined ecosystem services often concentrate on the 'actual value', consisting of: 'consumptive use value', 'non-consumptive use values' and 'indirect user values'. Hence, within these categories of values, it may make sense to talk about relative values and trade-offs, although often win-win opportunities can be found and no choice needs to be made (Costanza, 2020).

Moreover, in the literature we have identified a series of different environmental factors with relevance to soil biodiversity, biodiversity, fertiliser use, pesticide use, and irrigation water use (Balafoutis *et al.,* 2020). Rolandi *et al.* (2021) defined a total of four environmental impact areas, including 1) animal well-being, for which outcomes would include animal health and animal control, 2) ecosystem services for which outcomes would include biodiversity and climate, 3) natural resources, for which outcomes would include energy, nutrients, plant health, soil and water, and 4) risks-management for which outcomes would include prevention and proactivity. The concept of environmental costs and benefits is based on the hypothesis that nature is a major source of wellbeing for people. According to the Millennium assessment (2005) 'ecosystem services' can be classified into five types: provisioning, supporting, regulating, cultural. Provisioning and cultural services contribute directly to wellbeing in the form material and immaterial goods. Supporting (as carbon sequestration, water purification) and regulating (cycle of water and of the nutrients etc.) services allow the stability of the ecosystems. This means that the flows of provisioning and cultural services are related to the size and quality of regulating and supporting services.

Taking a complexity perspective to ecological values, benefits and costs are poorly understood, and poorly quantified, particularly in a long term (Costanza, 2020). According to ecological economics, ecosystems are named '**natural capital'** to highlight the role of ecosystems in the production and reproduction of ecosystem services, and to stress the importance of investments on natural capital to ensure an adequate flow of ecosystem services. In the socio-ecological system approach, ecosystems are named **'natural resource systems**' to highlight the instrumentality of nature to human subsystems. The framework also underpins the trade-offs that might be related to an imbalanced production of ecosystem services. Valuing natural capital or ecosystem services require understanding of a broader set of goals including ecological sustainability, social fairness and economic efficiency (Costanza, 2020). In such perspective the goal of valuation is not only to include individual, societal and ecosystem objectives of sustainable wellbeing for humans, but also for the rest of nature and the whole earth system (Costanza, 2020).

The assessment of the benefits and of the costs of digital technologies is therefore linked to the change of value attributed by different groups to the ecosystem services gain or loss. The complexity of this assessment is related to a different perception of the value of different types of ecosystem services, as the investments in natural capital might be accounted as costs for those who must trade immediate benefits with long-term benefits. Moreover, the assessment should be related not only to the farm level, but should take into account all environmental effects generated along with the life cycle of the technologies adopted. Life Cycle Assessment (LCA) can provide such an assessment by quantifying the impacts in 18 categories (e.g. Climate change, eutrophication, acidification etc) related to 3 areas of damages (human health, resource depletion and ecosystems). The values attributed to each category by the actors will be used to quantify the environmental costs and benefits.

4.6. Summing up

To improve our understanding of how costs and benefits of digital technologies are related to sustainability, in this chapter we investigated in this chapter what the costs and benefits are, and for whom. More precisely, we have illustrated that benefits and costs are complicated from a system perspective, and also when considering the social, economic and environmental costs separately. It is not clear what the benefits and costs are to whom, because a cost for one can be the benefit of another. Also, the multidimensionality of the sustainability concept put in a transitional situation cannot easily provide direct perception of costs and benefits of digitalisation because they will

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

differ across contexts, groups and individuals. However, understanding benefits and costs and their distributions of digitalisation is important, because this can help to identify appropriate policies.

First, from a system perspective, we address the differences between system outputs and system outcomes. Whereas system outputs are the direct and tangible results of a process, the aggregation of the multiple outputs in terms of costs and benefits provide the actual value to the system, which we refer to as outcomes. These outcomes will sooner or later cause impacts on the system. Following a socio-technical system approach, the costs and the benefits must be addressed according to some eight main entities, including 1) timeframe, context, 3) system needs, 4) system entities (who?), 5) system relationships (how?), 6) system activities (what?), 7) system expectations, and 8) impacts. The performances of costs and benefits in a digital ecosystem refer to the extent to which the context supports the growth and success of digital activities. The development of new technologies, the creation of new businesses, and the adoption of digital solutions can improve the conduciveness of the system. Components of external drivers of conduciveness of an ecosystem can be categories across social/cultural, technical/technological, economic/financial, environmental, and political drivers.

Second, from a social perspective, we address benefits and costs by first illustrating the difficulty of defining them. While it is possible to specify for instance consumers, employment or health care as social dimensions for the analyses, social analyses can alternatively focus on context specific impacts on: 1) individuals, for instance, on learning, 2) access to, for instance, resources or data, 3) rights such as equal rights, 4) social capital, such as trust and inclusion and 5) control, for instance, related with privacy. Moreover, social impacts differ if target group is an individual, a group, a community or an institution. Other social costs and benefits addressed in the literature refer to responsibilities, communication, collaboration, safety and problem solving, as well as cross-border collaboration and co-innovation, competition, education and acceptance. Further, social impacts can be about user readiness linked with internal drivers, like capabilities, opportunities and motivation, or social divide. To specify the arena to digitalisation, risk factors have been listed to the new developments of AI, which have been categories into individual, group, societal, economy, ecosystem, and value-norms related risks.

Third, from an economic perspective, the costs and benefits may be more straight forward. However, also for this category it gets complicated from a system perspective. This is because the benefits and costs differ and can be addressed in terms of productivity, services, and livelihood, or be associated with outcomes at organisational, value-chain or market areas. Following a business process perspective, the costs can be analysed according to productivity, quality of products, revenue, input costs, variable costs, crop wastage and energy use, but can also take into system costs to cover operational costs, transaction costs, transition costs, switching costs. Thinking along assessments broadly speaking, economic performances can be categorised into efficiency, effectiveness, transparency, credibility, accountability/legitimacy and inclusiveness.

Fourth, the environmental benefits and costs are also complicated, because the environment is a system itself, where all components are interdependent of interrelationships in terms of climate cycles, water cycles, nutrition cycles. The typology of environmental values can be categorised as benefits to nature and benefits to humans, non-use and use values, warm glow and existence values, option values and actual values, indirect and direct values, consumptive and non-consumptive values. As such, these dimensions are incommensurable, and show that some are not directly, but indirectly observed to relate with human wellbeing. Thinking of value-systems as intra-psychic constellations of norms and perceptions that guide human judgement and action, only some of the environmental values are considered.

In CODECS we concentrate on facilitating digitalisation of farms and minimise any corresponding risks, for so to increase farm productivity and efficiency, improve quality of work and reduce pressures to natural resources. From this perspective, CODECS identifies and accesses a full range of costs and benefits stemming from the adoption of digital technologies in farming. These costs and benefits can be environmental, economic and social and are viewed within CODECS as the decrease or increase of actors' capabilities to utilise resources. In CODECS, the environmental costs of digitalised production processes will be analysed through the methodological framework of a Life Cycle Assessment, a standardised method largely used in agriculture for assessing the environmental impact related to units of produced services. Economic costs are analysed through the estimation of technical and economic indicators, as well as of basic financial results at the farm - and system - level. When it is impossible or too complex to make quantitative assessment, especially when it comes to ecosystem services, social costs or immaterial benefits, qualitative or mixed indicator-based farm level assessments will be carried out.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

5. A synthesis - the CODECS Conceptual framework

5.1. The CODECS conceptual framework

The CODECS Conceptual framework (Figure 10) operates in an ever-changing contextual situation, impacted by external drivers, such as social, technical, environmental and political drivers, as well as internal drivers, such as capacities, motivations and opportunities. The external and internal drivers influence the contextual factors of entities, relationships and activities in a particular context. In CODECS we refer to a total of three main levels caused by digital changes to a specific context;

- At a first level, which can be referred to as a digitised socio-physical factors level, change is centred around digitisation at farm level, with implementation of sensing-actuation, business processes and farmer/user readiness, advancing the present basic context from before digitisation took place. At such a basic socio-physical factors level, the context of entities, relationships, and activities reflect a situation before the technology demonstrations are implemented in the CODECS' living labs, and the digitised socio-physical system refers to after the technology demonstration have been implemented.
- At a second level, which can be referred to as socio-cyber-physical system level, change is centred around digitalisation at digital ecosystem level, referring to system impacts following the demonstrations in the CODECS' living labs. This is because in a system, the demonstrations will not only have impacts at farm level but throughout a whole network. The rich literature available describes these dynamics in multiple ways.
- At a third level, which can be referred to as a transitioned socio-cyber-physical system level, change is caused by transition at a socio-ecological system level, based on outcomes at levels 1 and 2. This implies that the natural ecosystems, and governance systems are transitioning.

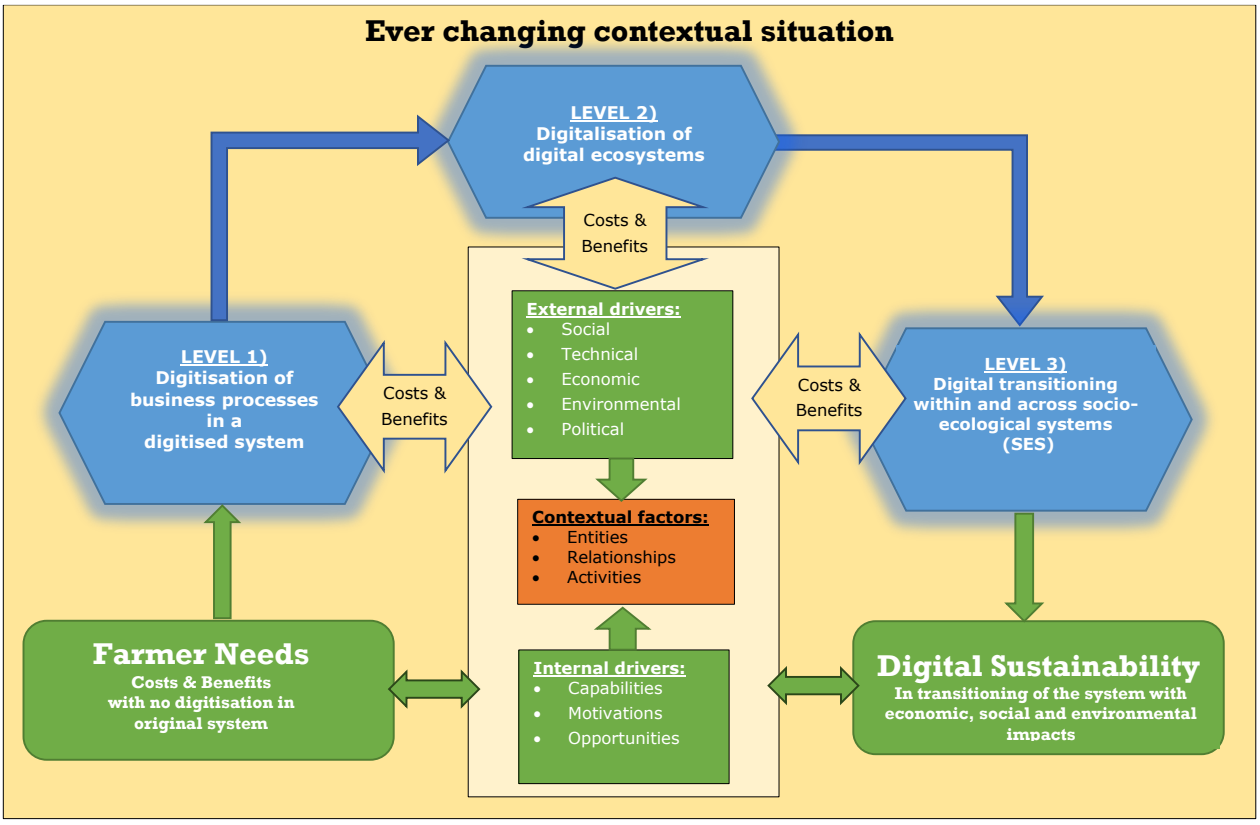


Figure 10 – CODECS Conceptual framework

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

At each of the three levels, the costs and benefits will differ in scope and character. While our starting point is the farmer needs, the transition refers to a societal context broadly speaking. Whereas level 1) begins with the farmer, level 2) includes the associated network to the farmers, and level 3) is not only at later time sequence, but hence covers the whole Socio-Ecological System (SES) a broader scope of the analyses involving interactions within and among natural ecosystems, and governance systems.

Hence, the design of such socio-cyber physical system comprises some three core critical components referred to as: design, access and complexity (Brunori, 2017). Design focuses on the challenges that the technology is supposed to deal with, as well as user needs and potential risks. A decision on a particular technology can have positive and negative impacts on sustainability issues, such as inclusion, exclusion of different societal groups in a socio-ecological system and can deal with the regulation ecosystem services, in particular. Access refers to infrastructure, human capital and financial resources, as well as human and system readiness levels, which can affect access conditions to the new technologies in different manners. These factors link us to the main causes of digital divide (van Dijk, 2020). Complexity describes the systemic conditions for adoption and scaling with digital technologies. This refers to interconnectedness in a well-functioning socio-cyber-technical network, with interoperability, which provide the opportunities for exchange, pool and integrate data between actors and devises. Complexities in a transitioned socio-cyber-technical system link with the natural and digital ecosystem components, as well as with the governance system, with implications for long term sustainability.

5.2. CODECS – four conceptual scenarios

The digitalisation of the agricultural sector in Europe, one of the risks with digitalisation is that small scale and regional farm systems and their technology suppliers or rural areas will be left behind and create low equity and inclusion (Soma *et al.,* 2019). Moreover, digitalisation taking place at global level is highly linked with enhancing services of global connectivity of goods, services, information, trade and people, whereas at local level digitalisation provides services of agricultural practices, effectiveness and efficiency in resource use, community development, inclusion of marginalised areas, digital divide, etc. Melville (2010) introduced a framework linking micro and macro levels by a so-called belief-action-outcome where social structure determines psychnic states with influence of individual and social systems behaviours. This is interesting because of the link made between individual and social system behaviours. In CODECS, macro-level refers to nations and Europe as a whole, whereas local to refer to specific communities and groups or regions. In Figure 11, the vertical axis refers to the two level, whereas the horizontal axis refers to low and high equity and inclusion.

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

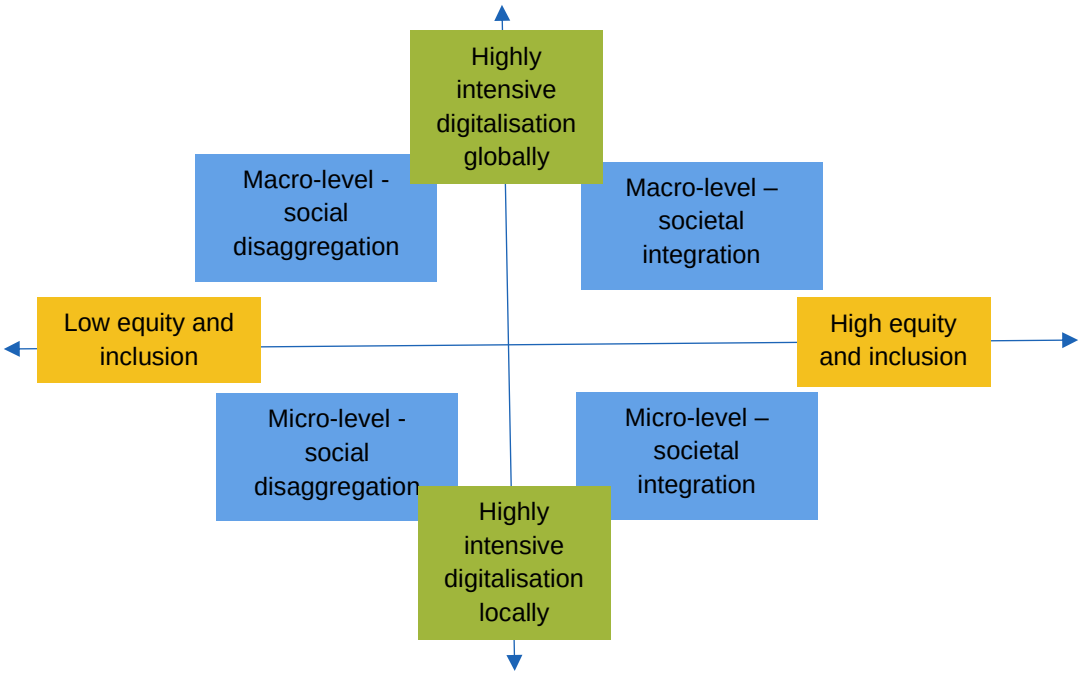


Figure 11 – CODECS four scenarios for digitalisation; 1) macro-level social disaggregation, 2) macro-level societal integration, 3) micro-level low social inclusion and 4) micro-level societal integration.

The combinations of the vertical and horizontal axis create a total of four scenarios, including macro-level social disaggregation and inclusion, as well as micro-level social disaggregation and inclusion. They are explained in the following.

Macro-level social disaggregation: While there is the potential for an overall cumulative increase in digitalisation globally, there is the possibility that this may still lead to low equity and poor social inclusion on a macro level. With increased digitalisation throughout Europe, some countries may be left behind. In a recent study, stakeholders were concerned that increased digitalisation in the agri-food domain would further exacerbate the digital divide between East and Western Europe (van der Burg and Ryan, 2021). In the agri-food domain, there was a lower adoption rate in Eastern European and Southern European countries, countries which are historically disadvantaged and underrepresented in European economics and politics. The reason for this low adoption of agri-food robots is due to the high investment and production costs, lack of digital structures for the robots to work on the farms, and low technology education levels (van der Burg and Ryan, 2021).

Employment and adequate levels of labour are significant issues being discussed in the literature on the topic of agri-food digitalisation and is a huge concern in the EU and globally (Carolan, 2020; Rose *et al.,* 2021; Klerkx *et al.,* 2019; Rodzalan *et al.,* 2020; Stock and Gardezi 2021; Ryan *et al.,* 2021; Sparrow and Howard, 2020; van der Burg *et al.,* 2019). For example, Sparrow and Howard (2020) claim that agri-food technologies, such as AI robots, may create a kind of disparity between the Global North and South because richer countries will be able to afford to deploy these technologies, while farmers in the South cannot (Fleming *et al.,* 2018; Ryan, 2019; van der Burg *et al.,* 2019). Further compounding these social inequalities is the fact that most farms in the South have female farmers of colour, while in the North it is predominantly white males. This very demographic holds the potential to further exacerbate the conditions of an already historically marginalised section of the population (women and people of colour). In addition, some also propose that increased digitalisation in agri-food holds the potential to worsen gender divisions in the domain. STEM (Science, Technology, Engineering and Mathematics) and agri-food have been historically male-dominated areas and the alignment of the two may further compound the low levels of women working in the area (Carolan, 2020; Sparrow and Howard, 2020).

Micro-level social disaggregation: While there is the potential for increasing digitalisation locally, without proper social inclusion and adequate equity distribution, this could lead to local social disaggregation. One foreseeable

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

impact of high digitalisation locally is that without implementing it in a balanced and inclusive way, certain communities and sections of the population will be hugely disadvantaged. While digitalisation in agri-food offers the potential to improve the well-being and livelihood of farmers, there is also the chance that certain farmers and groups of farmers will get 'left behind' (Rose *et al.,* 2021). For example, in the context of agri-food in Spain, many workers travel from Eastern Europe and North Africa to work in the fields for a few months per year, but with increased digitalisation, there is the possibility that their jobs will be replaced by agri-food robots (van der Burg and Ryan, 2021). In Europe, implementing high intensification of digitalisation in some regions poses a threat to other local communities that cannot afford to deploy and implement these technologies; there is the possibility that it will lead to a 'brain drain' because highly-skilled employees will move to the (digitalised) areas, offering higher pay; making it increasingly difficult for farmers in these communities to compete (van der Burg and Ryan, 2021).

Farmers may have to compete with robots for their jobs in the future (Ryan, *et al.,* 2021). Workers will be put under pressure to retrain or become computer technicians, to be able to manage the farm of the future (Rose *et al.* 2021, p. 307). There is also a concern that if farms become increasingly automated, they may be controlled from other locations (e.g., cities), leaving rural areas desolate and functioning simply as shells for agri-food production instead of communities (Sparrow and Howard, 2020, p. 825). The quality-of-life, sense of community, and culture of farmers may be lost as a result (Sparrow and Howard, 2020; Rose et al. 2021; Ryan, *et al.,*2021). Farmers may become simply 'caretakers' of robots, sensors, and digital tools on their farms (Ryan *et al.,* 2021; Ryan 2020), losing their sense-of-identity and purpose during the process (Sparrow and Howard, 2020, p. 826).

Macro-level social integration: There is the potential that increased digitalisation in the agri-food domain will bring increased macro level benefits, while also increasing equity and social inclusion. For example, some of the benefits of this kind of digitalisation may result in attracting younger workers to the sector (increased digitalisation in agri-food may make it techier and sexier), respond to a labour gap left by people leaving the sector, increase skilled jobs, and reduce the 'dull, dangerous, and dirty' jobs on the farm (Rose *et al.* 2021, p. 307). The EU plan '2030 Digital Compass: The European way for the Digital Decade' (EU, 2022). A successful implementation of the plan could empower citizens and businesses through a digital transformation of the economy and society at large. The result will be a transparent inclusion of digital sovereignty based on a strong ethical base, with respect for fundamental rights, the rule of law and democracy, inclusion, accessibility, equality, sustainability, resilience, security, improving quality of life, the availability of services and respect for citizens' rights and aspirations (Ciravegna *et al.,* 2024, forthcoming). By that a dynamic, resource-efficient, and fair economy and society evolves, where digitalisation of the economy or society is a critical underpinning of economic and societal resilience (EU, 2022). Combatting the digital divide is part of a digital transformation strongly supported by the scientific community. For policy, a macro-level of social integration depends on the ability to support the access to the digital; enhance education and digital literacy; improve socio-economic and socio-cultural conditions; stimulate community (e-)networks and strengthening the governance quality, for instance by improving the digital infrastructure (Ciravegna *et al.,* 2024, *forthcoming*).

Micro-level social integration: at the micro level, skills and capabilities are at the core of social integration, self-efficacy and actual abilities to use digital technology (Tsatsou, 2013). Actors can become more embedded through their interactions with others (Van Wijk *et al.,* 2019). Interactions allow and enable individuals to hear and understand others' viewpoints, stimulating reflexivity, challenging their taken-for-granted perspectives, and partially (or wholly) disembedding them from their governing institutional environment, creating room for new, innovative perspectives to enter their thinking and acting, and enhancing their engagement (Van Wijk *et al.,* 2019). As digitalisation is fundamental to the daily private, social and working life, it can serve as time-saving and empowering, increasing the individual capabilities, improve communications and transparency in procedures, create job opportunities and facilitate heavy work (Ciravegna *et al.,* 2024, forthcoming). By that citizens and local businesses can support the process of social integration. In the agro-food domain such micro-level social integration depends on specific attention to actions needed to support the social integration, such as education, local government support and collaboration within the chain of agri-food businesses.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

6. Policies for sustainable digitisation

6.1. Introduction

In this chapter we reflect on policies which can improve the capacity of digital technologies to achieve sustainability. Policies face new emerging challenges with transitions towards sustainable digitalisation. The rapid developments of new information technologies, information networks and social media are increasingly affecting societies around the world, including the transitioning of policy making, which can be addressed in two interrelated processes: on the one hand, new forms of governing through new forms and amounts of information, and on the other hand, through transformative changes in governance institutions due to the new information flows (Soma *et al.,* 2016a). New types of failures include (Weber and Roharacher, 2012); 1) infrastructural, given that the socio-physical system needs upgrading to become functional to the digitised socio-physical and the socio-cyber-technological systems, 2) institutional failure, including changes for fit not only on steering mechanisms in terms of regulation, standards and legislation, but also informally related with cultures, norm and values. 3) Interactions and network failures, related with on the one hand, too much interaction so the overview is hard to follow, and on the other hand low interactions caused by weak ties with other actors. 4) Capabilities failures appear when people do not know how to invest and how to reach specific goals. A system can further fail if lacking directionality, if miscalculating demands, and if policy coordination fails. For the latter, it is particularly important to ensure coherencies across national, regional, sectoral and technological levels.

CODECS intends to foster the development of capacities for assessing the contribution of agriculture to sustainability ambitions through the development of assessment approaches, analyses, and knowledge generation on the impacts, especially the costs, benefits and potential sustainability gains and losses, through the application of digital technologies. CODECS makes a significant contribution to establish a basis for the development, implementation and evaluation of sustainability- and data-related policies at regional, national and EU level and reaching related objectives, including Green Deal ambitions, the new CAP, and the 2030 Digital Compass.

Various policy developments are relevant to sustainable digitalisation in the European Union which address environmental, economic and social sustainability dimensions, including the Green Deal, the Common Agriculture Policy (CAP) and the digital initiative called '2030 Digital Compass: The European way for the Digital Decade'. For the more concrete policy measures, the EU's common agricultural policy (CAP) aims to support farmers and improve agricultural productivity, ensuring a stable supply of affordable food, safeguard EU farmers to make a reasonable living, help tackle climate change and the sustainable management of natural resources, maintain rural areas and landscapes across the EU, keep the rural economy alive by promoting jobs in farming, agri-food industries and associated sectors. CAP is a partnership agreement between agriculture and society, and between Europe and its farmers, and is managed and funded at European level from the resources of the EU's budget. Modernisation through knowledge exchange, innovation and digitalisation is explicitly underpinning all CAP objectives. Modernisation in agriculture and rural areas is an explicit horizontal objective of the CAP (EU Factsheet "A Greener and fairer CAP", 2021). It remains highly relevant to assess how the "farm-tech revolution" at different stages of digitalisation will impact the agricultural sector and in different ways disrupt modernisation of the Common Agricultural Policy (CAP) (Pesce *et al.,* 2019).

The European Green Deal includes multiple policy initiatives aiming at stimulating a green transition with the goal to reach climate neutrality in EU by 2050 and has been useful for placing digitalisation on the agenda. The European Commission (2019) encourages promotion and investments in digital technologies because they are essential enablers for transformation and changes, and also, attention is put on trade-offs between economic, environmental and social objectives. The Green Deal will make consistent use of all policy levers, including regulation and standardisation, investment and innovation, national reforms, dialogue with social partners and international cooperation. The European Pillar of Social Rights will guide action in ensuring that no one is left behind. (European Commission, 2019).

With the 2030 Digital Compass (EU, 2022), a vision for 2030 to empower citizens and businesses through a digital transformation called the 'Digital Decade' has been launched. This new policy initiative is a pathway to 'the digital transformation of the economy and society'. Central to the ambition is the aim of encompassing digital sovereignty in an open manner, respect for fundamental rights, the rule of law and democracy, inclusion, accessibility, equality,

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

sustainability, resilience, security, improving quality of life, the availability of services and respect for citizens' rights and aspirations. Moreover, it is designed to contribute to a dynamic, resource-efficient, and fair economy and society in the Union. The Digital Decade demonstrates overall that EU policy emphasises that digitalisation of the economy or society is a critical underpinning of economic and societal resilience.

The new CAP instructs to Member States to include their digitalisation strategies to be included in the National Strategic Plans by explaining how digitalisation can contribute to the CAP objectives. This instruction risks failing, because the Member States are expected to stick with supporting 'business as usual' and 'normal policies', which will not lead to any transition (Brunori, 2017). As mentioned above, business development with high tech can result in predominant weak or business-centred sustainability approach because of overall focus on customers' demands, the perspective of faster and more efficient and the understanding of digitisation as support to 'business as usual', with the result of acceleration of unsustainable growth (Niehoff, 2022). Transformative policies should instead address the root causes of emerging problems and give directionality to change. CODECS believes that the root causes can be fully understood if contextual factors as well as external and internal drivers are fully understood, at different stages of development. With this understanding it becomes possible to identify gaps and deal with real challenges hampering the digitisation pathways to a more sustainable agriculture context of Europe.

In this chapter, different approaches to address transformative policies from the literature are addressed briefly before sustainable digitalisation policies are addressed that are relevant to CODECS.

6.2. Transformative policies

Policies for sustainable digitalisation need to be transformative. In fact, they need to contribute to the development of new business processes, new digital ecosystems, and new socio-ecological systems. At farm level, decision making is made taking market forces such as prices and costs into account to develop resilient business models that can ensure profitability. Often these decision-making processes are short term, making use of advanced technologies to ensure higher profit margins. Although more often long-term decisions taking sustainability into account in farm decisions can result in reduced profit margin in a short term (Niehoff, 2022), it is the policy makers who should safeguard the long-term sustainability impacts (Janssen and Wimmer, 2015). This means that on-farm decisions that optimise the use of pesticides and fertiliser to the better to the business as well as to the environment, are not necessarily stimulating. For instance, multifunctionalities, agro-ecology and endurances of the broad spectre of ecosystem services, including the regulation and cultural ecosystem services, are not necessarily taken into account in farm decisions (Oostindie, 2018). There is thus a need for policy making to balance the social challenges and the climate and environmental challenges more broadly.

At a societal level, from an informational governance point of view, the digital transition with its extensive provisioning of information, have impacts through the whole policy environment. Transitioning takes place at multiple levels, including in the forms of information construction in policy processes, new relationships, transparency implications in environmental governance, new global arrangements and public engagement in the Information Age (Soma, 2016b).

Twin transition refers to promotion of both the digital transition and the energy transition (Benedetti *et al.,* 2023). Referring to a so-called Digital Economy and Society Index (DESI), it is clarified that the state of play of the twin transition across the Member states can be analysed by the core DESI dimensions including, human capital such as internet skills and advanced skills, connectivity such as WIFI, LoRa, 4G and 5G, integration of digital technology such as e-Commerce, and digital public governance such as e-government. In order to analyse the transformative innovation policy directly, the characteristics of transformative innovation policies can be analysed by common characteristics in terms of grand challenges and economic growth, directionality, multi-faceted policy interventions, multi-actors and global networks and multi-level governance (Haddad *et al.,* 2022). Moreover, the transition-oriented policies can be identified, which build on the common characteristics, and this can further be analysed by a so-called mission-oriented policy characterisation (*ibid.*). Relevant to digital transformation is also the concept of regionalisation. Regionalisation refers, on the one hand, to the processes of spatial ordering that influence change in policy activities across local, national and regional levels, and on the other hand, it is shaped by processes of cooperation and integration across territorial as well as political spaces (Soma *et al.,* 2016c).

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Experimental policy engagements, built around three different macroprocesses, are proposed as indicators for achieving transformative outcomes (Ghosh *et al.,* 2021). First, for building and nurturing niches as a macro-process, the transformative outcomes can be measured in terms of offering protection for niche experiments, inducing first and second order learning for niche experiments, creating high -quality opportunities for collaboration between actors, and creating spaces for articulating expectations around social challenges and enhance credibility, stability and quality. Second, for the macro process of expanding and mainstreaming niches, the transformative outcomes can be observed as upscaling by increasing adoption by users of new emerging systems, replicating by internationally facilitating replication of niche experiments, circulating by identifying and promoting ideas, people and technologies, and institutionalising by mainstreaming the rules of the niches (behaviour, beliefs and values). Third, the macro-process of opening up and unlocking regimes facilitating developments of disruptive policy arrangements, facilitating deep learning among actors, creating links between niches and contextual factors, and facilitating processes to challenge individual and collective perceptions about e.g. how digitalisation can contribute to climate action.

Another way of analysing the transformative intent of policy is to refer to a so-called X-Curve of transition build-up and break down to reach at transitional socio-technical systems (Lazarevik *et al.,* 2022). Such transition involves a starting point with experimentation, and through institutionalisation, a point of stabilisation in reached at the new level. However, a parallel process of destabilisation of the old system will take place, which eventually will break down, leading to a phase out. Within such transitional phases, there will be an inherent power struggle of different actors, because power relations may change through transitioning processes (Callon, 1984).

In CODECS transformative policies are understood in terms of three main characteristics: a) directionality; b) reflexivity; c) market integration (Brunori, 2022).

- Directionality implies that policies are coordinated around clear directions of change. This implies a 'policy mix' approach, that address the system components in a coherent and consistent way. Directionality is also underpinned by effective strategies, which set the values, the principles, the goals, and the tools for change.
- Reflexivity implies a learning-by-doing approach to policies. Transformative policies foster social, institutional, business innovation at different levels and adopt procedures to learn from experience and embody lessons learned into the policy cycle.
- Market integration implies an understanding of how policies affect socio-economic configurations. If policy measures generate high costs and low benefits, for example, there is the risk of policy failure.

Each of the three characteristics of transformative policies can be implemented through specific policy tools. For example, directionality is supported by research and innovation policies, by the setting up of science-policy interfaces, by information and communication. Reflexivity is developed through the creation of institutional circuits that facilitate the knowledge exchange between policymakers and stakeholders. Market integration is pursued through regulation, taxes, incentives, and in general by all measures aimed at affecting actors' behaviour.

6.3. Sustainable digitalisation policies in CODECS

CODECS operates at three main levels; the business process level, the digital ecosystem level and the socio-ecological system level. A higher level of organisation constitutes the context for the lower-level providing rules, resources, and constraints to them. Components of lower levels cannot control directly higher levels but can affect them as the aggregated effects of the outputs of their activities. The performance of each level affects the performance of the others. For example, when a process makes use of natural resources, it generates pressure on the socio-ecological system. The socio-ecological system has a given carrying capacity, beyond which the cumulative pressure of processes generates instability in the system. The analysis of the processes helps to identify how, where and by whom costs and benefits are generated, suggesting the points where action can be taken to improve the performance of the system.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

The CODECS Conceptual framework can help to structure digitalisation strategies that address the three levels of analysis considered above. Table 5 provides an example on how policies can affect the three levels.

Table 5 – Policy tools for transformative policies

	Directionality	Reflexivity	Market integration
Business processes	Technical standards, training	Interactive innovation, policy evaluation	Support to investments, contribution to costs
Digital ecosystems	Digital strategies, innovation policies, AKIS governance, education policies, support to investments in infrastructures	Interactive innovation, education, training, policy evaluation	Support to investments, contribution to costs
Socio-ecological systems	Science-policy-society interfaces, territorial strategies, environmental regulation, resource governance systems	Interactive innovation, education, policy evaluation, monitoring tools	Support to investments, contribution to costs, payment of ecosystem services

In CODECS we assume that policies are dynamic processes characterised by cycles of different phases, including the problem definition phase, the agenda setting phase, the policy design phase and the implementation phase:

- In the problem definition phase, the role of politics is crucial, as it provides the values, the principles, the interests at stake and affect the perception of the problem. When knowledge is uncertain, different values, principles and interests generate disagreement on the goals or on the actions to achieve them. Knowledge can contribute to 'structure' the problem, creating certainty on facts and encouraging the emergence of shared goals and values. On this regard, the role of science (society)-policy interfaces has been highlighted as a policy tool help policymakers to 'structure' the problems through generation of evidence-based consensus.
- In the agenda-setting phase, priorities are identified. Also, in this case politics has an important role, and the role of knowledge is related to the capacity to provide arguments and evidence to demonstrate the urgency of policy measures.
- In the policy design phase, the role of elective bodies, high-level public officers and experts is prevalent. Given the structure of the problem, policymakers tend identify the policy tools that can achieve the goals while minimising costs, limit conflicts between different interests, and are able to gain consensus.
- In the implementation phase, policies are applied in different contexts, and their effectiveness depends on how policy measures are turned into actors, rules, resources and artifacts within the specific local configurations.

For the socio-cyber physical system level in the CODECS Conceptual framework, which is beyond the CODECS time frame, but before the final transitional stage that is aimed for following the SDGs, the following activities can have positive impacts.

First, the problem definition phase, which took place across technology demonstrations at farm level across the 20 living labs in CODECS, addressed issues of equal data access, digital poverty, increased inequalities and cyber security, as well as risks of affecting environmental resources and climate negatively. In this way the problem definitions phase can contribute positively to future sustainable digitalisation. Notably, the scope and specifications depend on contextual factors, and level of policy making across local, national, EU-regional, and international levels.

Second, the knowledge generated throughout the CODECS can eventually benefit the agenda setting for future policy making at a digital ecosystem level, because the knowledge of risks of costs and benefits have been estimated.

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Third, the outcomes of the analyses across the different work packages and throughout the living labs will provide proven scientific insights, which ideally will support the policies aiming at sustainable digitalisation in complex contexts, to make sure policy implementation can trigger more than hamper the transitioning towards the SDGs by enhancing social, environmental and economic benefits at all levels, and reducing costs. As such, the following impact areas of economic integration, as well as environmental, governance and social areas of operation, can benefit with policies based on directionality, reflexivity and market integration.

Vik *et al.* (2021) developed a balanced readiness assessment methodology at an organisational level, for which the technology readiness level (TRL) assessment is expanded to include market readiness level, regulatory readiness level, acceptance readiness level and organisational readiness level. While this is an interesting development of the commonly used TRL, in CODECS the organisational coverage would still be too limited. Therefore, in CODECS a sustainability assessment approach is currently being developed for digitalisation, with an expansion to a coverage of social, societal, environmental, economic as well as technological readiness.

6.4. Summing up

In this chapter we have reflected on policies which can improve the capacity of digital technologies to achieve sustainability. CODECS intends to foster the development of capacities for assessing the contribution of agriculture to sustainability ambitions through the development of assessment approaches, analyses, and knowledge generation on the impacts, especially the costs, benefits and potential sustainability gains and losses, through the application of digital technologies. CODECS makes a significant contribution to establish a basis for the development, implementation and evaluation of sustainability- and data-related policies at regional, national and EU level and reaching related objectives, including Green Deal ambitions, the new CAP, and the 2030 Digital Compass.

The literature provides different ways of analysing transformative policies. For instance, twin transition may be analysed based on human capital, connectivity, integration of digital technologies as well as digital policies. At macrolevel, it may be more appropriate to base analyses on development by specifying; 1) building and nurturing niches as macro-process, expanding and mainstreaming niches for upscaling and adoption, as well as opening up and unlocking regimes. Moreover, a so-called X-curve transition with building-up and breaking-down as parallel transitioning and destabilising processes can both be needed for the analyses of the sustainable transition towards sustainable digitalisation. Finally, the factors of directionality referring to policy coordination, reflexivity referring to learning and market integration referring to understanding of how policies affect socio-economic configurations are of high relevance to CODECS,

At the socio-cyber physical system level in the CODECS Conceptual framework, which is beyond the CODECS time frame, but before the real transitional stage aiming at the SDGs, the following activities can have positive impacts. First, the problem definition phase can benefit from the research activities that took place across the demonstrations at farm level across the 20 living labs, and second, the knowledge generated throughout the CODECS can eventually benefit the agenda setting for future policy making at a digital ecosystem level, because the knowledge of risks of disadvantages in costs and benefits have been estimated. Third, the outcomes of the analyses across the different work packages and throughout the living labs will provide proven insights scientifically, which will support the policy in complex contexts, to make sure policy implementation can trigger more than hamper the transitioning towards the SDGs by enhancing social, environmental and economic benefits at all levels, and reducing costs.

7. Theory of change for CODECS

In this chapter, a Theory of Change is presented to give a brief overview of the CODECS' activities and how they result in relevant outputs, contributing to outcomes, impacts and the goal of sustainable digitalisation. Based on the visioning of CODECS broadly speaking, linking development and adoption of digital technologies for sustainability

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

outcomes, a theory of change has been developed based on an online web meeting with consortium members (Figure 12). The theory of change demonstrates that the main goal of CODECS is to contribute to sustainable digitalisation, with coverage of economic, environmental and social sustainability. To reach to this end, CODECS has defined that the desired outcome of this project is to reach at improved understanding of costs and benefits broadly speaking, thus covering advantages and disadvantages not always considered in analyses of costs and benefits. The outputs of CODECS will give insights into the extents to which different costs and benefits can contribute to the desired outcomes and the main goal. The many activities carried out across the different work packages in CODECS, and across all the 20 living labs, are directed towards reaching at more insights about the costs and benefits (outputs), which can give invaluable insights about the costs and benefits of the digitisation with intention to reach the main goal of CODECS. To ensure that all the activities will serve their purposes, a set of conditions are needed in terms of a relevant problem definition in the living labs, the appropriate qualifications of the research team and the co-creation among the consortium members.

Goal. In the Theory of Change, the main goal has been defined "Sustainability in digital ecosystems", and a selection of relevant SDGs have been listed. On the one hand, three main human organisational related SDGs have been listed, including; 1) Decent work and economic growth, in particular to promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all (SDG8), 2) industry, innovation and infrastructure to build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation (SDG9) and 3) sustainable cities and communities to make cities and human settlements inclusive, safe, resilient and sustainable (SDG11). On the other hand, a total of three main natural resource related SDGs have been listed, including; 1) Clean sanitation and water to ensure availability and sustainable management of water and sanitation for all (SDG6), 2) responsibility to ensure sustainable consumption and prosecution patterns (SDG12), and 3) life on land to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss (SDG15). These are not exclusive to CODECS, because all SDGs will be relevant to context specific digitalisation processes, it is rather a shortlist of examples. The literature provides advise on whether sustainable digitalisation has been achieved, for instance, Wolfert and Isakhanyan (2022) developed a practitioner's approach to monitor sustainability progress, consisting of a total of five steps; 1) define target SDGs, 2) define KPIs and functional units, 3) define baseline and target values, 4) Identify measurement method, and 5) monitor the progress.

Impacts. Some four main impact areas have been defined in CODECS. First, with reference to policy, CODECS will contribute to improved desired sustainability in policy making at national and EU levels, as a pathway towards reaching the SDGs in context specific environments. Second, CODECS will contribute to improved business contexts for scaling and business development, as a pathway towards reaching the SDGs in context specific environments. Third, CODECS will contribute to increased capabilities across multiple actors to innovate and invest, as a pathway towards reaching the SDGs in context specific environments, and fourth, CODECS will contribute to enhanced opportunities for transdisciplinary in research developments as a pathway towards reaching the SDGs in context specific environments.

Outcomes. The outcomes can be seen as mirroring the impacts. First, CODECS will contribute to new opportunities for policy making ensuring sustainability in resource use and conduciveness of context, and second, CODECS will contribute to shared understanding of critical factors enabling good business environment and business actions towards sustainability. Third, CODECS will contribute to enhance knowledge level of multi-actors about opportunities for digitalisation and societal risks involved, and fourth, CODECS will contribute to Adoption of a broader perspective of sustainability impacts of digitalisation in Europe.

Outputs. In linking development and adoption of digital technologies for sustainability outcomes, the main outputs of CODECS can be listed as; 1) The CODECS Conceptual framework, policy analyses and the CODECS platform, guidelines and handbooks, as well as scientific articles, 2) analyses results of 20 living focal actions situations with mapping of socio-ecological contexts, including ecosystems and governance systems, 3) showcases of 20 living lab demonstrating performance and sustainability, enhanced network of demo farms and new demonstration forms, and 4) estimated social, economic and environmental benefits and costs, and the living lab stakeholders' perceptions.

Activities. The activities in CODECS are multiple and interrelated at different levels, and in this section, it is only possible to cover a share of main activities. We concentrate a total of four activity streams which have been active during the first part of the project.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

First, a sequence of activities in CODECS relate with co-creation of shared vision, framework, methodology, as well as reviews of existing and propose new policy tools and government patterns. The co-creation sessions arranged were important in the beginning of the project when a series of informal meetings were held to get familiar with different concepts and methods to be used across the tasks and work packages, and how they would link and contribute separately and jointly. Attached to these informal meetings, a living document was co-created by project partners across the different work packages and tasks leads to explain more in detail what the theoretical and methodological bases of the activities they planned to be carried out would look like. In this way, it was possible to connect different lines of activities, which all have contributed to the CODECS Conceptual framework presented in this deliverable. The CODECS Conceptual framework is targeting European policy making, and as such the goals and intentions with Green deal, the new CAP and the 2030 Digital Compass, among others.

The CODECS Conceptual framework conceptually links the different levels and activities and arrangements across the work plan of CODECS. The CODECS Conceptual framework operates in an ever-changing contextual situation, impacted by external drivers, such as social, technical, environmental and political drivers, as well as internal drivers, such as capacities, motivations and opportunities. The external and internal drivers influence the contextual factors of entities, relationships and activities in a particular context. In CODECS we refer to a total of three main levels caused by digital changes to a specific context; 1) At a first level, change is centred around digitisation, with implementation of sensing-actuation, business processes and user readiness, advancing the present context from a basic level of socio-physical factors to a situation with digitised socio-physical factors 2) At a second digital ecosystem level, with socio-cyber-physical factors, change is centred around digitalisation, referring to system impacts following the demonstrations. 3) At a third level, change is caused by transitioned socio-cyber-physical system, with outcomes of digitisation at farm level, impacting the farming networks, made visible throughout the whole socio-ecological system. This implies that the natural and digital ecosystems, governance systems, the resource units and the actors are interrelating in non-linear manners, leading to transitioning.

Second, investigation across living labs about resources, capabilities, conduciveness and readiness in focal action situation will take place. This includes that in each focal action situation across the 20 living labs must be identified a clear problem statement, together with its resources, capabilities, collaborations, and innovations (RCCIs) that exist and contribute to solving the main problem/challenge. This is followed by recognising how the four subsystems of Ostrom´s framework (governance systems, actors, resource units and resource systems) enable those RCCIs needed for solving the problem. Subsequently, the subsystems in the socio-ecological system (SES) approach must be understood because they determine conduciveness/readiness. Based on this, specific/general indicators which suggest digital ecosystem conduciveness and farmer readiness are identified. Establishing a conducive “digital ecosystem” applicable to agriculture requires an enabling environment, willingness, and readiness by the parties involved, which is investigated in CODECS.

In order to navigate some of this complexity, business process modelling, focusing on its relevance and application for social scientists and economy experts, will be carried out. Business process models are a specific type of system model that represents the sequence of activities, decisions, and resources involved in accomplishing a business objective providing a visual representation of how work is performed within an organisation, highlighting dependencies, inputs, outputs, control flows, and system modelling. CODECS will also carry out system modelling as a method used to represent and analyse complex systems. It involves creating abstractions of real-world systems, allowing stakeholders to gain insights into their structure, behaviour, and interactions. By using graphical or textual notations, system models capture the essential elements and relationships within a system, facilitating a holistic understanding of its dynamics. Moreover, process models will be carried out by analyses of the processes before and after the introduction of digital technologies in the context of the foal action situations (FASs) as defined by each living lab. This method is referred to as a so-called Farm Socio-technical Process Modelling of Use Cases. This is a qualitative analysis which develops an infographic of the system envisioned by each living lab by describing actors, resources, technological innovations, and relations thereof. In order to provide a complete overview of the processes relevant to the definition of the socio-ecological system, processes are mapped over the entities and relationships of Ostrom’s framework, thus considering the information required by Ostrom, e.g., actors, resource units, input, inclusion, and participation relationships. Moreover, the analyses provide qualitative inputs to the cost-benefit analysis.

Third, CODECS will support technology demonstrations on (demo-) farms, conducting on-farm demo activities, constructing virtual demos, and showcase of digital technology performances. The 20 CODECS living labs will carry

CODECS has received funding from the European Union’s Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

out demonstration events and arrange a number of events referred to as on-farm, cross-visits and virtual events that each living lab must implement. First, this involves a total of 40 on-farm demos for the whole project, comprising two on-farm demos per living lab to introduce participants to a given technology. This is, on the one hand, to capture the expectations and perceptions of costs and benefits of the demonstrated technology and the digital ecosystem where the technologies are implemented, and the other hand, to provide the participants with feedback from the cost-benefit analyses as well as the digital ecosystem activities. Moreover, a total of 10 international cross-visits for the whole project is foreseen during the whole project period, to increase cross-border peer-to-peer learning and exchange knowledge and practices about a given technology in a similar or different digital ecosystem. Also, a total of 20 virtual demos for the whole project are required, which is one virtual demo per living lab, to showcase a digital technology implemented in each living lab demo farm through an online website (thanks to Videos, PPT, virtual tours and other means), and to incentivise collective reflection and knowledge exchange and gather participant's feedback.

Fourth, CODECS will ensure data is collected in the 20 living labs to analyse stakeholder perceptions, environmental, economic and social costs and benefits. The data will be used in a series of sustainability analyses, including the analyses of environmental impacts of the use of digital technologies at farm level, the analyses of economic costs and benefits, as well as the analyses of the social/human-centred costs and benefits of digitalisation at farm level.

Environmental impact analyses will be carried out in the living labs to analyse relevant environmental impacts produced during the life cycle of a product, process or service, from the extraction of primary materials through production, use and to the end-of-life treatment of the product. Commonly, about 18 impact categories are described (mid points) which can then be combined in 3 damage categories (Human health, Ecosystem and Resources)

For the analyses of the economic costs and benefits, CODECS focuses on the main level of the economic analyses at farm level where decision making regarding the adoption of digital technologies primarily takes place and where resources and other system components interact to provide outcomes. Depending on the specific FAS examined, the economic analyses will also focus on the process level or provide information at the system level. Economic costs derive from the combination and use of tangible (e.g. land and capital) and intangible (e.g. knowledge, management skills and collaborations) resources to provide outcomes. The economic costs included in the analyses cover transition costs i.e., initial investment costs required for the adoption of digital technologies, as well operation costs i.e. annual production costs. To take into account the socio-economic environment where decision making takes place, scenario analyses and/or stochastic analyses will be utilised, at least in some focal action situations where data is availability.

For the analyses of the social/human-centred costs and benefits of digitalisation at farm level, the CODECS objective is to delve deeper into the social consequences of digital technologies in agriculture, focusing on the intangible aspects induced by their use. By doing so, we aim to gain a comprehensive understanding of their effects on farmers and farming practices. This is to expand research efforts to include the social dimension of digital technologies, which is vital for a more comprehensive understanding of their role in shaping a better world, particularly in the context of digital agriculture. By considering the broader social implications and incorporating users' perspectives and experiences, we will pave the way for effective and sustainable integration of these technologies in the agricultural sector. In particular, social/human-centred costs and benefits of digitisation at the farm level will be evaluated, mainly by identifying and enhancing the understanding of the use of digital technologies by farmers.

Pre-conditions. The core preconditions for CODECS to be successful in carrying out the tasks and eventually receive impacts in a long term, depend on some core factors, including sustainability as shared vision, good collaboration and trust among project partners and a safe working environment for researchers and different partners, as well as partnership with core stakeholders.

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

THEORY OF CHANGE

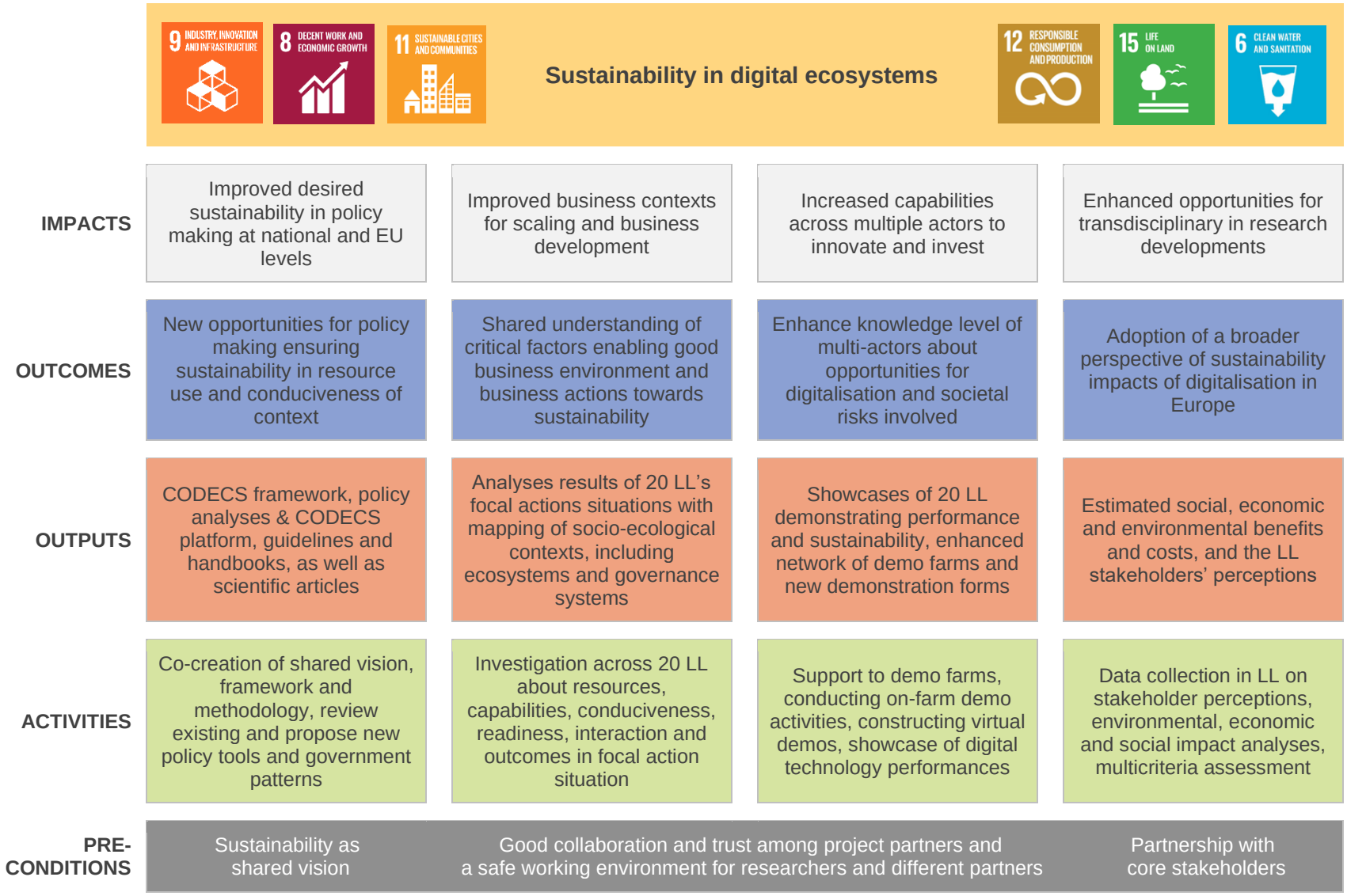


Figure 12 – Theory of change for CODECS

Funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation Programme under Grant Agreement n. 101060179. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

8. Concluding remarks and future research

Positive assumptions about social, economic and environmental sustainability impacts with digitalisation of the European agricultural sector are frequently shared on the policy and research agendas across Europe. However, there is a clear knowledge "gap" between the portfolio of digital technologies offered at the market and the actual uptake and use by farmers in the EU. Moreover, there is little knowledge about the actual reduction of negative environmental and climate effects due to their application. In CODECS it is acknowledged that digitalisation in agriculture can generate benefits as well as costs, and can contribute to sustainability, but with main concerns about potential risks; 1) if benefits will not necessarily overcome costs, and 2) if costs and benefits will not necessarily be distributed equally. In order to address these risks, it is crucial to approach digitalisation in the agricultural sector in Europe from a system perspective and define a CODECS theoretical framework which can improve understanding of the complexities of the transition towards sustainable digitalisation in Europe.

In CODECS, addressing the **links between digital technologies and sustainability**, it is defined that for CODECS the term 'sustainable digitalisation' is understood as a process of social transformation by which digital technologies are embodied into socio-economic life to promote intra-generational, inter-generational, inter-species wellbeing, reduce inequalities, and improve the health of ecosystems. Moreover, the term 'digital technology provision' is addressed by referring to, among others, digitalisation, sensing, actuation, computing and intelligence. It is explained that the process of representing the physical world through numbers is called 'digitisation', and the process of digital transformation is thus referred to as 'digitalisation'. Hence, relevant follow-up research questions about sustainable transition pathways include:

- How do digital technologies change the actors, the rules, the artifacts, the resources of agricultural activities?
- How are digital technologies assembled in agriculture?
- How are different assemblages affecting the outputs of agricultural activities?

CODECS operates at three levels for the analyses: 1) business processes, 2) digital ecosystems and 3) socio-ecological systems levels. **Business process level** refers to farm related processes as they are, and farm related processes as they become after digitisation, i.e., after the introduction of the technology, whereas **digital ecosystem level** is defined as an organised set of digital, socio-economic, organisational, and physical components that support the production, storage, communication, elaboration, and use of digital technologies and data. A digital ecosystem provides the resources necessary to support the digitalisation of processes at digital ecosystem level: connectivity infrastructures, organisational resources, human resources, knowledge, data, and platforms. The analysis of digital ecosystems focuses primarily on networks and infrastructures, which link together actors and artifacts through relations, activating the flow of resources and stimulating learning and innovation. The original Ostrom framework approach of **socio-ecological systems (SES)** assesses the sustainability of natural resources through the analysis of the drivers that generate pressures on them. On this regard, the framework states that human activities (actors´ subsystem) use resource units (assets used by actors in agriculture and rural economies) in their processes. To assess the sustainability of the processes, it is to be considered that resource units are encompassed by resource systems, therefore, resource systems are made up of interlinked resource units, including social, economic, technological, and environmental assets. The actors (individual and collective) carry out activities involved inhabit particular contexts, with their own interests, ambitions, capabilities, access to resources, knowledge levels, and beliefs. Human activities are regulated by rules and norms generated by governance systems. Governance systems are structured through constitutional rules, contractual arrangements, accountability systems, strategic exercises, traditions and routines. As governance systems define, in the last instance, the distribution of the costs and benefits of human processes, they are the dynamic outcomes of power relations between the actors that compose them, and it is not rare that rules generated by governance systems are not coherent with each other.

The reviews about technology- sustainability linkages, the three levels of business processes, digital ecosystems, and socio-ecological systems, as well as the costs and benefits of a digital ecosystem from a system perspective, have developed building stones to the formulation of the CODECS Conceptual framework. The CODECS Conceptual framework is addressing an ever-changing contextual situation, with external drivers, such as social,

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

technical, environmental, and political drivers, as well as capabilities, motivations, and opportunities as internal drivers. The external and internal drivers influence the contextual factors such as the entities, the relationships and the activities taking place. In CODECS we refer to the three main levels of causing changes to the context:

1) Business processes with digitisation through implementations of sensing-actuation, business processes and user readiness, contribute to increase from a basic level of socio-physical factors to a situation with digitised socio-physical factors. Whereas the socio-physical system refers to the starting point with no digitisation, a context of entities, relationships, and activities the way we know it before the demos in the living labs, and the digitised socio-physical system refers to the living labs after the technology demonstration at farm level. Linking technology with sustainability, relevant research questions to business processes include:

- What are the characteristics and outputs of the system 'as-is'?
- Who are the stakeholders of the process? Who sets its goals?
- What are the gaps of the system in term of efficiency, effectiveness, transparency, innovation?
- What technological solutions are available to address the gaps?
- What are the user readiness and the scaling readiness of the available solutions?
- What are the characteristics and expected outputs and benefits of the 'to-be' system?
- What are the costs and the risks of adopting the 'to-be' system?

2) Digital ecosystems with digitalisation because of system impacts of the demonstrations, for in a system the demonstrations will not only have impacts at farm level but the whole network. The rich literature describes this socio-cyber-physical system in multiple ways, where digital ecosystems, AKIS and system readiness create the playground for the contextual factors. Linking technologies with sustainability, relevant research questions related with digital ecosystems include:

- What are the relevant components (resources, capabilities, collaborations, and innovations (RCCIs) of digital ecosystems in specific agri-rural contexts?
- What roles do specific actors/organisations/ the Ostrom´s subsystems play in digital ecosystems?
- What are the components (RCCIs and AKIS), relations, and roles that contribute to conduciveness of the ecosystem?
- To what extent, in the specific context, do AKIS, RCCIs and the Ostrom´s subsystems link ecological and digital transitions? Are they enablers or factors of resistance to change?
- To what extent are actors ready to transform digitally their farms?
- How might digitalisation affect AKIS role as knowledge intermediaries?
- To what extent can AKIS actors act as change agents regarding institutional and business actors?

3) The third level of transitioning brings us to yet another level referred to as the transitioned socio-cyber-physical system. Here the outcomes are made visible throughout the whole socio-ecological system, including the natural ecosystems, and governance systems. Linking technologies with sustainability, relevant research questions to socio ecological systems (SES) include:

- How does digitalisation contribute to the sustainability of the socio-ecological system?
- How does digitalisation affect natural resource systems?
- How does the four Ostrom´s subsystems of the socio-ecological system affect the conduciveness of digital ecosystems?
- What is the potential of specific Focal Action Situations in transforming the socio-ecological-technical system?

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

With the application of digital technologies, CODECS intends to foster the development of capacities for assessing the contribution of agriculture to sustainability ambitions through the development of assessment approaches, analyses, and knowledge generation on the impacts, especially the costs, benefits and potential sustainability gains and losses. Investigating **costs and benefits of digital technologies related to sustainability**, the complexity of it is illustrated from a system perspective, and also by reviewing social, economic and environmental costs separately. Following a socio-technical system approach, the costs and the benefits must be addressed according to some eight main entities, including: 1) timeframe, context, 3) system needs, 4) system entities (who?), 5) system relationships (how?), 6) system activities (what?), 7) system expectations, and 8) impacts. From a social perspective, benefits and costs can be addressed, for instance, linked with consumers, employment or health care, or be defined across: 1) individuals, 2) access, 3) rights, 4) social capital, and 5) control. In the area of digitalisation, user readiness can be linked with internal drivers, like capabilities, opportunities and motivation, or social divide, or with risk factors, which have been categories for individual, group, societal, economy, ecosystem, and value-norms related risks. From an economic perspective, the costs and benefits may be more straight forward, but still it gets complicated from a system perspective. Following a business process perspective, the costs can be analysed according to productivity, quality of products, revenue, input costs, variable costs, crop wastage and energy use, but can also take system costs to cover operational costs, transaction costs, transition costs, and switching costs into account. Thinking along assessments broadly speaking, economic performances can be categorised into efficiency, effectiveness, transparency, credibility, accountability/legitimacy and inclusiveness. From the environmental context, benefits and costs are highly complicated because the environment is a system where all components are interdependent of interrelationships in terms of climate cycles, water cycles and nutrition cycles, which defined the existence of it, but are not directly valued. The typology of environmental values, categorised as benefits to nature and benefits to humans, non-use and use values, warm glow and existence values, option values and actual values, indirect and direct values, consumptive and non-consumptive values. Relevant follow-up research questions to investigate the social, environmental, and economic outcomes of the introduction of digital technologies into farm processes, include:

- How changes in the process affect ecosystem services?
- How changes in the process affect social relations and different social groups?
- How do different social groups and individuals value the outcomes of the introduction of digital technologies?

While some of these research questions fall out of the scope of CODECS and the living lab activities, in CODECS we concentrate on facilitating digitalisation of farms and minimise any corresponding risks and, thus, to increase farm productivity and efficiency, improve quality of work and reduce pressures to natural resources. From this perspective, CODECS identifies and access a full range of costs and benefits stemming from the adoption of digital technologies in farming. These costs and benefits can be environmental, economic, and social and are viewed within CODECS as the decrease or increase of actors' capabilities to utilise resources. In CODECS, the environmental costs of digitalised production processes will be analysed through the methodological framework of a Life Cycle Assessment, a standardised method now largely used in agriculture which will assess the environmental impact related to units of produced services. Economic costs are analysed through the estimation of technical and economic indicators as well as of basic financial results at the farm - and system - level. When it is impossible or too complex to make quantitative assessment, especially when it comes to ecosystem services, social costs or immaterial benefits, qualitative or mixed indicator-based farm level assessments will be carried out.

Policies can improve the capacity of digital technologies to achieve sustainability by building on outputs of CODECS to contribute to establish a basis for the development, implementation and evaluation of sustainability- and data-related policies at regional, national and EU levels, reaching related objectives, including Green Deal ambitions, the new CAP, and the 2030 Digital Compass. The literature provides different ways of analysing transformative policies. For instance, twin transition may be analysed based on human capital, connectivity, integration of digital technologies as well as digital policies. At macrolevel, it may be more appropriate to base analyses on development by specifying; building and nurturing niches as macro-process, expanding and mainstreaming of niches for upscaling and adoption, as well as opening up and unlocking regimes. Moreover, a so-called X-curve transition build-up and break-down as parallel transiting and destabilising processes, which both are needed in sustainable transitioning towards sustainable digitalisation. Finally, and highly relevant to CODECS, the factors of directionality referring to

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

policy coordination, reflexivity referring to learning and market integration referring to understanding how policies affect socio-economic configurations are relevant. The outcomes of the analyses across the different work packages and throughout the living labs will provide proven insights scientifically, which will support future policy implementation in complex contexts, to make sure policy implementation can trigger more than hamper the transitioning towards the SDGs by enhancing social, environmental, and economic benefits at all levels, and reducing costs. In order to contribute to more insights about social, economic and environmental costs and benefits of digitalisation, the following research questions are of relevance:

- Do the existing trends of digitalisation in agriculture correspond to the sustainable digitalisation criteria?
- How to assess sustainable digitalisation of agriculture? How to measure it?
- How to conciliate the different dimensions of sustainability when promoting digitalisation of agriculture?

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

References

Abbate, S., Centobelli, P., Cerchione, R. (2023). The digital and sustainable transition of the agri-food sector. Technological Forecasting and Social Change, 187, 122222.

Ackoff, R. 1971. Towards a system of system concepts. Management Science 17:11, 661-671.

Adhikari, J., Mathrani, A., Scogings, C. (2021). Analysis of technology-mediated pedagogies: Experiences from a BYOD initiative in New Zealand. 2021 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE), 1–6. https://doi.org/10.1109/CSDE53843.2021.9718393

Aissaoui, N. (2022). The digital divide: A literature review and some directions for future research in light of COVID-19. Global Knowledge, Memory and Communication, 71(8/9), 686–708. https://doi.org/10.1108/GKMC-06-2020-0075

Ayris, K., Jackman, A., Mauchline, A., Rose, D. C. (2024). Exploring inclusion in UK agricultural robotics development: who, how, and why?. Agriculture and Human Values, 1-19.

Autio, E. Digitalisation, Ecosystems, Entrepreneurship and Policy; Policy Briefs; Finland Ministry of Trade and Employment: Helsinki, Finland, 2017.

Bacco, M., Barsocchi, P., Brunori, G., Debruyne, L., Ferrari, A., Gotta, A., ... Toli, E. (2020b). D1. 3 Synthesis report on the Taxonomy and Inventory of Digital Game Changers. Zenodo. DOI: https://doi. org/10.5281/zenodo, 4556849.

Bacco, M., Barsocchi, P., Ferro, E., Gotta, A., Ruggeri, M. (2019). The digitisation of agriculture: a survey of research activities on smart farming. Array, 3, 100009.

Bacco, M., Brunori, G., Ferrari, A., Koltsida, P., Toli, E. (2020a). IoT as a digital game changer in rural areas: The DESIRA conceptual approach. In 2020 Global Internet of Things Summit (GIoTS) (pp. 1-6). IEEE.

Baker, J. (2012). The technology–organization–environment framework. Information Systems Theory: Explaining and Predicting Our Digital Society, Vol. 1, 231-245.

Balafoutis, A. T., Evert, F. K. V., Fountas, S. (2020). Smart farming technology trends: economic and environmental effects, labor impact, and adoption readiness. Agronomy, 10(5), 743.

Barab, S. (2014). Design-based research: A methodological toolkit for engineering change. The Cambridge handbook of the learning sciences, 2, 151-170.

Barnes, A. P., Soto, I., Eory, V., Beck, B., Balafoutis, A., Sánchez, B., ... Gómez-Barbero, M. (2019). Exploring the adoption of precision agricultural technologies: A cross regional study of EU farmers. Land use policy, 80, 163-174.

Barnett, M. L. (2006). The keystone advantage: what the new dynamics of business ecosystems mean for strategy, innovation, and sustainability.

Benbya, H., Nan, N., Tanriverdi, H., Yoo, Y. (2020). Complexity and information systems research in the emerging digital world. Mis Quarterly, 44(1), 1-17.

Benedetti, I., Guarini, G., Laureti, T. (2023). Digitalisation in Europe: A potential driver of energy efficiency for the twin transition policy strategy. Socio-Economic Planning Sciences, 89, 101701.

Benson, T. (2019). “Digital Innovation Evaluation: User Perceptions of Innovation Readiness, Digital Confidence, Innovation Adoption, User Experience and Behaviour Change.” BMJ Health and Care Informatics 26 (1). doi:10.1136/bmjhci-2019-000018.

Bradu, P., Biswas, A., Nair, C., Sreevalsakumar, S., Patil, M., Kannampuzha, S., ... , Gopalakrishnan, A. V. (2023). Recent advances in green technology and Industrial Revolution 4.0 for a sustainable future. Environmental Science and Pollution Research, 30(60), 124488-124519.

Brouwer, I. D., McDermott, J., Ruben, R. (2020). Food systems everywhere: Improving relevance in practice. Global food security, 26, 100398.

Brown, L. R. (1970). The social impact of the green revolution. Int'l Conciliation, 39, 3.

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

Brundtland, G. H. (1987). Our common future—Call for action. Environmental conservation, 14(4), 291-294.

Brunori, G. (2022). Agriculture and rural areas facing the “twin transition”: principles for a sustainable rural digitalisation. Italian Review of Agricultural Economics, 77(3), 3-14.

Bucci, G., Bentivoglio, D., Belletti, M. and Finco, A., 2020. Measuring a farm's profitability after adopting precision agriculture technologies: A case study from Italy. Acta IMEKO, 9(3), pp.65-74.

Callon, M. (1984). Some elements of a sociology of translation: domestication of the scallops and the fishermen of St Brieuc Bay. The sociological review, 32(1_suppl), 196-233.

Caragliu, A., Del Bo, C. F. (2022). Smart cities and urban inequality. Regional Studies, 56(7), 1097–1112.

Charatsari, C., Michailidis, A., Francescone, M., De Rosa, M., Aidonis, D., Bartoli, L., ... Lioutas, E. D. (2023). Do Agricultural Knowledge and Innovation Systems Have the Dynamic Capabilities to Guide the Digital Transition of Short Food Supply Chains?. Information, 15(1), 22.

Ciravegna, E., Selnes, T., Soma, K. *Submitted.* Unraveling a multifaceted digital divide in Europe: a systematic literature review. The European Journal Of Social Science Research. *Submitted.*

Clancy, K., 2013. Feedback loops. J. Agric. Food Syst. Community Dev. 3, 5–7. https://doi.org/10.5304/jafscd.2013.033.007

Coquil, X., Cerf, M., Auricoste, C., Joannon, A., Barcellini, F., Cayre, P., ... Prost, L. (2018). Questioning the work of farmers, advisors, teachers and researchers in agro-ecological transition. A review. Agronomy for Sustainable Development, 38, 1-12.

Corradini, F., Ferrari, A., Fornari, F., Gnesi, S., Polini, A., Re, B., Spagnolo, G. O. (2018). A guidelines framework for understandable BPMN models. Data and Knowledge Engineering, 113, 129-154.

Costanza, R. (2020). Valuing natural capital and ecosystem services toward the goals of efficiency, fairness, and sustainability. Ecosystem Services, 43, 101096.

Criado, J. I., Gil-Garcia, J. R. (2019). Creating public value through smart technologies and strategies: From digital services to artificial intelligence and beyond. International Journal of Public Sector Management, 32(5), 438-450.

Cruz-Jesus, F., Vicente, M. R., Bacao, F., Oliveira, T. (2016). The education-related digital divide: An analysis for the EU-28. Computers in Human Behavior, 56, 72–82. https://doi.org/10.1016/j.chb.2015.11.027

Damtew, E., Douthwaite, B., Schut, M., Sartas, M., Leeuwis, C. (2023). Improving Scaling Performance in Research for Development: Learning from a Realist Evaluation of the Scaling Readiness Approach. The European Journal of Development Research, 1-27.

Delvenne, P. (2017). Responsible research and innovation as a travesty of technology assessment? Journal of Responsible Innovation, 4(2), 278-288.

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., ... Zlatanova, D. (2015). The IPBES Conceptual Framework—connecting nature and people. Current opinion in environmental sustainability, 14, 1-16.

Elena-Bucea, A., Cruz-Jesus, F., Oliveira, T., Coelho, P. S. (2021). Assessing the Role of Age, Education, Gender and Income on the Digital Divide: Evidence for the European Union. Information Systems Frontiers, 23(4), 1007–1021. https://doi.org/10.1007/s10796-020-10012-9

Emmi, L., Gonzalez-de-Soto, M., Pajares, G., Gonzalez-de-Santos, P. (2014). Integrating sensory/actuation systems in agricultural vehicles. Sensors, 14(3), 4014-4049.

Ericksen, P.J., 2008. Conceptualizing food systems for global environmental change research. Global Environ. Change 18, 234–245. https://doi.org/10.1016/j.gloenvcha. 2007.09.002.

EU (2021/2115). EU Regulation 2021/2115 of The European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the common agricultural policy (CAP Strategic Plans). (EU) No 1305/2013 and (EU) No 1307/2013. OJ L 435, 6.12.2021, p. 1–186.

CODECS has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

Ferrari, A., Bacco, M., Gaber, K., Jedlitschka, A., Hess, S., Kaipainen, J., Koltsida, P., Toli, E., Brunori, G. (2022). Drivers, barriers and impacts of digitalisation in rural areas from the viewpoint of experts. Information and Software Technology, 145, p.106816.

Fielke, S., Bronson, K., Carolan, M., Eastwood, C., Higgins, V., Jakku, E., ... , Wolf, S. A. (2022). A call to expand disciplinary boundaries so that social scientific imagination and practice are central to quests for 'responsible'digital agri-food innovation. Sociologia Ruralis, 62(2), 151-161.

Gangwar, D.S., Tyagi, S. Soni, S.K. (2022). A techno-economic analysis of digital agriculture services: an ecological approach toward green growth. International Journal of Environmental Science and Technology, 19(5), pp.3859-3870.

Ghosh, B., Kivimaa, P., Ramirez, M., Schot, J., Torrens, J. (2021). Transformative outcomes: assessing and reorienting experimentation with transformative innovation policy. Science and Public Policy, 48(5), 739-756.

Giller, K. E., Delaune, T., Silva, J. V., Descheemaeker, K., van de Ven, G., Schut, A. G., ... van Ittersum, M. K. (2021). The future of farming: Who will produce our food?. Food Security, 13(5), 1073-1099.

Giua, C., Materia, V. C., Camanzi, L. (2022). Smart farming technologies adoption: Which factors play a role in the digital transition? Technology in Society, 68, 101869. https://doi.org/10.1016/j.techsoc.2022.101869

Gottfredson, L.S. 1997. Mainstream science on intelligence: An editorial with 52 signatories, history, and bibliography. Intelligence, 24, 13–23.

Greenwood, J. The Third Industrial Revolution: Technology, Productivity, and Income Inequality; The AEI Press: Washington, DC, USA, 1997.

Gugganig, M., Burch, K. A., Guthman, J., Bronson, K. (2023). Contested agri-food futures: Introduction to the Special Issue. Agriculture and Human Values, 40(3), 787-798.

Guzzo, D., Walrave, B., Videira, N., Oliveira, I. C., Pigosso, D. C. (2024). Towards a systemic view on rebound effects: Modelling the feedback loops of rebound mechanisms. Ecological Economics, 217, 108050.

Haddad, C. R., Nakić, V., Bergek, A., Hellsmark, H. (2022). Transformative innovation policy: A systematic review. Environmental Innovation and Societal Transitions, 43, 14-40.

Hassani, H., Silva, E. S., Unger, S., TajMazinani, M., Mac Feely, S. (2020). Artificial intelligence (AI) or intelligence augmentation (IA): what is the future?. Ai, 1(2), 8.

Hennessy, T., Läpple, D., Moran, B. (2016). The Digital Divide in Farming: A Problem of Access or Engagement? Applied Economic Perspectives and Policy, 38(3), 474–491. https://doi.org/10.1093/aepp/ppw015

Hess, C., Ostrom, E (Eds). 2007. Understanding Knowledge as a Commons: From Theory to Practice. The MIT Press. pp 382. https://www.jstor.org/stable/j.ctt5hhdf6

Horlings, L. G., Marsden, T. K. (2011). Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could 'feed the world'. Global environmental change, 21(2), 441-452.

Howlett, M., Ramesh, M., Perl, A. (1995). Studying public policy: Policy cycles and policy subsystems (Vol. 3). Toronto: Oxford university press.

IAASTD, E. (2009). Agriculture at a Crossroads. International Assessment of Agricultural Knowledge, Science and Technology for Development, Synthesis Report No. HD1428. I547 2008.

Iansiti, M., Levien, R. (2004). Strategy as ecology. Harvard business review, 82(3), 68-78.

Iansiti, M., Richards, G. L. (2006). The information technology ecosystem: Structure, health, and performance. The Antitrust Bulletin, 51(1), 77-110.

IPOL. 2019. Regulating working conditions through EU directives – EU employment law outlook and challenges. Policy Department for Economic, Scientific and Quality of Life Policies. European Parlement. Briefing PE 638.430.

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Jabłoński, A., Jabłoński, M. (2022). Intelligent Digital Transformation in Modern Socio-Technical Systems–A Sustainable Approach. In Intelligent Systems in Digital Transformation: Theory and Applications (pp. 55-73). Cham: Springer International Publishing.

Jacobides, M., A. Sundararajan, M. Van Alstyne (2019) Platforms and Ecosystems: Enabling the Digital Economy. World Economic Forum, https://www3.weforum.org/docs/WEF_Digital_Platforms_and_Ecosystems_2019.pdf

Janssen, M., Wimmer, M. A. (2015). Introduction to policy-making in the digital age. Policy practice and digital science: Integrating complex systems, social simulation and public administration in policy research, 1-14.

Kahneman, D. 2011. Thinking, Fast and Slow; Penguin Books Ltd.: London, UK.

Kernecker, M., Busse, M., Knierim A. (2021). Exploring actors, their constellations, and roles in digital agricultural innovations. Agricultural Systems, 186, 102952.

Klerkx, L., Jakku, E., Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS-Wageningen journal of life sciences, 90, 100315.

Kurtsal, Y., Rinaldi, G. M., Savini, F., Sirri, R., Melin, M., Pacetti, E., ... Viaggi, D. (2024). Improving the Education and Training Policies of the Agri-Food and Forestry Sectors: Identifying New Strategies to Meet the Needs of the Sector and Farm-to-Fork Priorities. Sustainability, 16(3), 1267.

Kvam, G. T., Hårstad, R. M. B., Stræte, E. P. (2022). The role of farmers' microAKIS at different stages of uptake of digital technology. The Journal of Agricultural Education and Extension, 28(5), 671-688.

Lacombe, C., Couix, N., Hazard, L. (2018). Designing agroecological farming systems with farmers: A review. Agricultural systems, 165, 208-220.

Larsson, A., Viitaoja, Y. (2019). Identifying the digital gender divide: How digitalisation may affect the future working conditions for women. In The digital transformation of labour (pp. 235-253). Routledge.

Latour, B. (1987). Science in action: How to follow scientists and engineers through society. Harvard university press.

Lazarevic, D., Salo, H., Kautto, P. (2022). Circular economy policies and their transformative outcomes: The transformative intent of Finland's strategic policy programme. Journal of Cleaner Production, 379, 134892.

Leimeister, J. M., Österle, H., Alter, S. (2014). Digital services for consumers. Electronic Markets, 24, 255-258.

Lolich, L., Pirhonen, J., Turja, T., Timonen, V. (2022). Technology in the Home Care of Older People: Views from Finland and Ireland. Journal of Cross-Cultural Gerontology, 37(2), 181–200. https://doi.org/10.1007/s10823-022-09449-z

Lowenberg-DeBoer, J., Erickson, B. (2019). Setting the record straight on precision agriculture adoption. Agronomy Journal, 111(4), 1552-1569.

Macaya, J. F. M., Ribeiro, M. M., Jereissati, T., dos Reis Lima, C., Cunha, M. A. (2021). Gendering the digital divide: The use of electronic government services and implications for the digital gender gap. Information Polity, 26(2), 131–146. https://doi.org/10.3233/IP-200307

Mäkitie, T., Hanson, J., Damman, S., Wardeberg, M. (2023). Digital innovation's contribution to sustainability transitions. Technology in Society, 73, 102255.

Marangunić, N., Granić, A. (2015). Technology acceptance model: a literature review from 1986 to 2013. Universal access in the information society, 14, 81-95.

Maroufkhani, P., Wagner, R., Wan Ismail, W. K. (2018). Entrepreneurial ecosystems: A systematic review. Journal of Enterprising Communities: People and Places in the Global Economy, 12(4), 545-564.

Martens, K., Zscheischler, J. (2022). The Digital Transformation of the Agricultural Value Chain: Discourses on Opportunities, Challenges and Controversial Perspectives on Governance Approaches. Sustainability, 14(7), 3905. https://doi.org/10.3390/su14073905

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

Maye, D., Kirwan, J., Brunori, G. (2019). Ethics and responsibilisation in agri-food governance: the single-use plastics debate and strategies to introduce reusable coffee cups in UK retail chains. Agriculture and human values, 36, 301-312.

Mburu, J., Börner, J., Hedden-Dunkhorst, B., Mendoza-Escalante, A., Frohberg, K. (2007). Feasibility of mulching technology as an alternative to slash-and-burn farming in eastern Amazon: A cost–benefit analysis. Renewable Agriculture and Food Systems, 22(2), pp.125-133.

McCampbell, M., Adewopo, J., Klerkx, L., Leeuwis, C. (2023). Are farmers ready to use phone-based digital tools for agronomic advice? Ex-ante user readiness assessment using the case of Rwandan banana farmers. The Journal of Agricultural Education and Extension, 29(1), 29-51.

McMahon, R., Akçayır, M. (2022). Investigating concentrated exclusion in telecommunications development: Engaging rural voices from Northern Canada. Journal of Rural Studies, 95, 183–194. https://doi.org/10.1016/j.jrurstud.2022.09.004

Melville, N. P. (2010). Information systems innovation for environmental sustainability. MIS quarterly, 1-21.

Metta, M., Ciliberti, S., Obi, C., Bartolini, F., Klerkx, L., Brunori, G. (2022). An integrated socio-cyber-physical system framework to assess responsible digitalisation in agriculture: A first application with Living Labs in Europe. Agricultural Systems, 203, 103533.

Michie, S., West, R., Rogers, M. B., Bonell, C., Rubin, G. J., Amlôt, R. (2020). Reducing SARS-CoV-2 transmission in the UK: A behavioural science approach to identifying options for increasing adherence to social distancing and shielding vulnerable people. British Journal of Health Psychology, 25(4), 945-956.

Millennium Ecosystem Assessment. (2005). Ecosystems and human well-being: Synthesis. Island Press.

Martinez-Alier, J., Munda, G., O'Neill, J., (1998). Weak comparability of values as a foundation for ecological economics. Ecological Economics 26, 277–286.

Mondejar, M. E., Avtar, R., Diaz, H. L. B., Dubey, R. K., Esteban, J., Gómez-Morales, A., ... Garcia-Segura, S. (2021). Digitalisation to achieve sustainable development goals: Steps towards a Smart Green Planet. Science of The Total Environment, 794, 148539.

Moreddu, C., Poppe, K. J. (2013). Agricultural research and innovation systems in transition. EuroChoices, 12(1), 15-20.

Mulla, D., Gregorio Lopez, E., Llorens Calveras, J., Lopez, A., De Castro, A., Biswas, A., ... Stenberg, B. (2021). Sensing approaches for precision agriculture. R. Kerry, A. Escolà (Eds.). Cham, Switzerland: Springer International Publishing.

Munda G. (2004). 'Social Multi-criteria Evaluation (SMCE): Methodological Foundations and Operational Consequences', European Journal of Operational Research, 3: 662–77.

Munz, J. (2024). What if precision agriculture is not profitable?: A comprehensive analysis of the right timing for exiting, taking into account different entry options. Precision Agriculture, pp.1-40.

Munz, J. Schuele, H. (2022). Influencing the success of precision farming technology adoption—A model-based investigation of economic success factors in small-scale agriculture. Agriculture, 12(11), p.1773.

Mutenje, M.J., Farnworth, C.R., Stirling, C., Thierfelder, C., Mupangwa, W. Nyagumbo, I. (2019). A cost-benefit analysis of climate-smart agriculture options in Southern Africa: Balancing gender and technology. Ecological Economics, 163, pp.126-137.

Niehoff, S. (2022). Aligning digitalisation and sustainable development? Evidence from the analysis of worldviews in sustainability reports. Business strategy and the environment, 31(5), 2546-2567.

Nussbaum, M. C. (2007). Capabilities as fundamental entitlements: Sen and social justice. In Capabilities equality (pp. 54-80). Routledge.

OECD. (2015). Fostering Green Growth in Agriculture. The Role of Training, Advisory Services and Extension Initiatives. OECD Green Growth Studies, OECD Publishing, Paris. https://doi.org/10.5367/oa.2015.0194

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

OECD (2018) Bridging The digital Gender divide: Include, upskill, Innovate. Paris: OECD

Oostindie, H. (2018). Unpacking Dutch multifunctional agrarian pathways as processes of peasantisation and agrarianisation. Journal of rural studies, 61, 255-264.

Ostrom, E. 2007. A diagnostic approach for going beyond panaceas. Proceedings of the national Academy of sciences. 104, 15181-15187.

Ostrom, E., 2009a. A general framework for analyzing sustainability of social-ecological systems. Science, 325; 419-422.

Ostrom, E., 2009b. Understanding Institutional Diversity. Princeton University Press, Princeton, pp. 376.

Ostrom, E., 2011. Background on the institutional analysis and development framework. Policy studies journal, 39, 7-27.

Pariso, P., Marino, A. (2020). From digital divide to e-government: Re-engineering process and bureaucracy in public service delivery. Electronic Government, an International Journal, 16(3), 314. https://doi.org/10.1504/EG.2020.108495

Patel, R. (2013). The long green revolution. The Journal of Peasant Studies, 40(1), 1-63.

Peltoniemi, M., Vuori, E. (2004, September). Business ecosystem as the new approach to complex adaptive business environments. In Proceedings of eBusiness research forum (Vol. 2, No. 22, pp. 267-281).

Perifanou, M., Economides, A. (2020). Gender Digital Divide in Europe. International Journal of Business, Humanities and Technology, 10(4). https://doi.org/10.30845/ijbht.v10n4p2

Pesce M., Kirova M., Soma K., Bogaardt M-J., Poppe K., Thurston C., Monfort Belles C, Wolfert S., Beers G., Urdu D. (2019). Research for AGRI Committee – Impacts of the digital economy on the food-chain and the CAP, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels. https://www.europarl.europa.eu/RegData/etudes/STUD/2019/629192/IPOL_STU(2019)629192_EN.pdf

Pinto, F., Macadar, M. A., Pereira, G. V. (2022). The potential of eParticipation in enlarging individual capabilities: A conceptual framework. Information Technology for Development, 1–23. https://doi.org/10.1080/02681102.2022.2136129

Pretty, J., Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. Annals of botany, 114(8), 1571-1596.

Ramos, J., Soma, K., Bergh, Ø., Schulze, T., Gimpel, A., Stelzenmüller, V.,... (2015). Multiple interests across European coastal waters: the importance of a common language. ICES Journal of Marine Science 72 (2), 720-731

Ranchordás, S. (2022). The Digitisation of Government and Digital Exclusion: Setting the Scene. In C. Blanco de Morais, G. Ferreira Mendes, T. Vesting (Eds.), The Rule of Law in Cyberspace (Vol. 49, pp. 125–148). Springer International Publishing. https://doi.org/10.1007/978-3-031-07377-9_7

Riddlesden, D., Singleton, A. D. (2014). Broadband speed equity: A new digital divide? Applied Geography, 52, 25–33. https://doi.org/10.1016/j.apgeog.2014.04.008

Rijswijk, K., Klerkx, L., Bacco, M., Bartolini, F., Bulten, E., Debruyne, L., ... Brunori, G. (2021). Digital transformation of agriculture and rural areas: A socio-cyber-physical system framework to support responsibilisation. Journal of Rural Studies, 85, 79-90.

Rolandi, S., Brunori, G., Bacco, M., Scotti, I. (2021). The digitalisation of agriculture and rural areas: Towards a taxonomy of the impacts. Sustainability, 13(9), 5172.

Sacco, P., Gargano, E. R., Cornella, A. (2021). Sustainable digitalisation: A systematic literature review to identify how to make digitalisation more sustainable. In International TRIZ Future Conference (pp. 14-29). Cham: Springer International Publishing.

Sartas, M., Schut, M., Proietti, C., Thiele, G., Leeuwis, C. (2020). Scaling Readiness: Science and practice of an approach to enhance impact of research for development. Agricultural Systems, 183, 102874.

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Schwab, K. The Fourth Industrial Revolution; Crown Business: New York, NY, USA, 2017.

Sen, A. 1985. Commodities and Capabilities. Amsterdam: North-Holland.

Sen, A. 1999. Development as Freedom. New York: Knopf.

Senyo, P. K., Liu, K., Effah, J. (2019). Digital business ecosystem: Literature review and a framework for future research. International journal of information management, 47, 52-64.

Sheu, M., Kim, H. (2009). User readiness for is development: An examination of 50 cases. Systems Research and Behavioral Science: The Official Journal of the International Federation for Systems Research, 26(1), 49-61.

Silva, D. S., Yamashita, G. H., Cortimiglia, M. N., Brust-Renck, P. G., ten Caten, C. S. (2022). Are we ready to assess digital readiness? Exploring digital implications for social progress from the Network Readiness Index. Technology in Society, 68, 101875. https://doi.org/10.1016/j.techsoc.2022.101875

Soma, K. (2006). Natura economica in environmental valuation. Environmental Values, 15(1), 31-50.

Soma, K. (2010). Framing participation with multicriterion evaluations to support the management of complex environmental issues. Environmental Policy and Governance, 20, 89-106.

Soma, K., Ramos, J., Bergh, Ø., Schulze, T., van Oostenbrugge, H., ... (2014). The “mapping out” approach: effectiveness of marine spatial management options in European coastal waters. ICES Journal of Marine Science 71 (9), 2630-2642

Soma, K., MacDonald, B. H., Termeer, C. J., Opdam, P. (2016b). Introduction article: informational governance and environmental sustainability. Current Opinion in Environmental Sustainability, 18, 131-139.

Soma, K., Onwezen, M. C., Salverda, I. E., van Dam, R. I. (2016c). Roles of citizens in environmental governance in the Information Age—four theoretical perspectives. Current Opinion in Environmental Sustainability, 18, 122-130.

Soma, K., Termeer, C. J., Opdam, P. (2016a). Informational governance–A systematic literature review of governance for sustainability in the Information Age. Environmental Science and Policy, 56, 89-99.

Spada, P., Mellon, J., Peixoto, J., Sjoberg, F. M. (2015). Effects of the Internet on Participation—Study of a Public Policy Referendum in Brazil. World Bank Group. http://hdl.handle.net/10986/21643

Sutherland, L. A., Adamsone-Fiskovica, A., Elzen, B., Koutsouris, A., Laurent, C., Stræte, E. P., Labarthe, P. (2023). Advancing AKIS with assemblage thinking. Journal of Rural Studies, 97, 57-69.

Sutherland, L. A., Burton, R. J., Ingram, J., Blackstock, K., Slee, B., Gotts, N. (2012). Triggering change: Towards a conceptualisation of major change processes in farm decision-making. Journal of environmental management, 104, 142-151.

Szeles, M. R., Simionescu, M. (2020). Regional Patterns and Drivers of the EU Digital Economy. Social Indicators Research, 150(1), 95–119. https://doi.org/10.1007/s11205-020-02287-x

Thornton, P. K., Schuetz, T., Förch, W., Cramer, L., Abreu, D., Vermeulen, S., Campbell, B. M. (2017). Responding to global change: A theory of change approach to making agricultural research for development outcome-based. Agricultural Systems, 152, 145-153.

Tirado-Morueta, R., Rodríguez-Martín, A., Álvarez-Arregui, E., Ortíz-Sobrino, M. Á., Aguaded-Gómez, J. I. (2021). The digital inclusion of older people in Spain: Technological support services for seniors as predictor. Ageing and Society, 1–27. https://doi.org/10.1017/S0144686X21001173

Tomblin, D., Mogul, N. (2020). STS Postures: responsible innovation and research in undergraduate STEM education. Journal of Responsible Innovation, 7(sup1), 117-127.

Tsatsou, P. (2013). Digital inclusion: a case for micro perspectives. Digital world: Connectivity, creativity and rights, 52-63.

UN AI advisory body (2023) Interim report: governing AI for humanity. https://www.un.org/sites/un2.un.org/files/ai_advisory_body_interim_report.pdf

Co-funded by the European Union

CODECS has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

UN. Transforming Our World: The 2030 Agenda for Sustainable Development Resolution Adopted by the General Assembly on 25 September 2015. Available online: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E (accessed on 4 September 2020).

Valkokari, K. (2015). Business, innovation, and knowledge ecosystems: How they differ and how to survive and thrive within them. Technology innovation management review, 5(8).

Van der Burg, S., Bogaardt, M. J., Wolfert, S. (2019). Ethics of smart farming: Current questions and directions for responsible innovation towards the future. NJAS-Wageningen Journal of Life Sciences, 90, 100289.

Van Wijk, J., Zietsma, C., Dorado S., de Bakker, F.G.A., Martí, I. (2019). Social Innovation: Integrating Micro, Meso and Macro Level Insights From Institutional Theory. Business and Society 2019, Vol. 58(5) 887–918. DOI: 10.1177/0007650318789104

Vasile, V., Panait, M., Apostu, S.-A. (2021). Financial Inclusion Paradigm Shift in the Postpandemic Period. Digital-Divide and Gender Gap. International Journal of Environmental Research and Public Health, 18(20), 10938. https://doi.org/10.3390/ijerph182010938

Vik, J., Melås, A. M., Stræte, E. P., Søraa, R. A. (2021). Balanced readiness level assessment (BRLa): A tool for exploring new and emerging technologies. Technological Forecasting and Social Change, 169, 120854.

Vuorikari, R., Jerzak, N., Karpinski, Z., Pokropek, A. Tudek, J. (2022). Measuring Digital Skills across the EU: Digital Skills Indicator 2.0, EUR 31193 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-55856-9, doi:10.2760/897803, JRC130341.

Weber, K. M., Rohracher, H. (2012). Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework. Research policy, 41(6), 1037-1047.

Williams, K., Chatterjee, S., Rossi, M. (2008). Design of emerging digital services: a taxonomy. European journal of information systems, 17(5), 505-517.

Wohed, P., van der Aalst, W. M., Dumas, M., ter Hofstede, A. H., Russell, N. (2006). On the suitability of BPMN for business process modelling. In Business Process Management: 4th International Conference, BPM 2006, Vienna, Austria, September 5-7, 2006. Proceedings 4 (pp. 161-176). Springer Berlin Heidelberg.

Wolfert, S., Isakhanyan, G. (2022). Sustainable agriculture by the Internet of Things–A practitioner's approach to monitor sustainability progress. Computers and Electronics in Agriculture, 200, 107226.

Wolfert, S., Bogaardt, M. J., Ge, L., Soma, K., Verdouw, C. (2017). Guidelines for governance of data sharing in agri-food networks. In 7th Asian-Australasian Conference on Precision Agriculture, Zenodo. https://doi. org/10.5281/zenodo (Vol. 893700).

World Economic Forum. (2016). Internet for All - A Framework for Accelerating Internet Access and Adoption. WEF.

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Appendix 1. Overview of CODECS living labs

Table A11 – Overview of a total of 20 living labs in CODECS

Living Lab	Country	Application scenario	Expected benefits	Problem solving	Technology (TRL)
• **Pecorino Toscano DOP**	Italy, Tuscany	Extensive dairy sheep farms	To improve the quality of production, the quality of work and the life of farmers, the visibility of the farm and the animal health and welfare	Facilitating farmers in the data collection of data related to farm processes.	Farm Management Information System (FMIS) – TRL6
• **Greenhouse smart sensor lab**	Serbia	Vegetable greenhouse production	To increase yield and preventing damage and plant stress induced by low or high temperatures in greenhouses, reduce the use of water and increase agricultural production.	Monitoring the conditions in the greenhouse (soil moisture, soil water potential, soil pH, air temperature/humidity, leaf wetness sensor, photosynthetically active radiation sensor, CO2 sensor)	IoT sensors node, combine with a web platform suitable for pc, tablet and smartphone – TRL 7
• **Organic Table Grape**	Italy, Puglia	Organic table grape production	To increase the quality and quantity of organic table grape production by reducing the qualitative and quantitative pressure on the soil and water resources	Managing the key factors of production: irrigation, fertilisation patterns, pest and disease control	Sensors in orchard at field level (soil, environment, and crop) interconnected and in communication with a Decision Support System (DSS) – TRL 8

Living Lab	Country	Application scenario	Expected benefits	Problem solving	Technology (TRL)
• **Appetit Living Lab**	Poland	Short food chains	To grow local markets, decrease transaction costs and increase benefits of virtual and physical market-place interactions between buyers and sellers in a defined geographical space	Providing and automate "intermediary services" essential for connecting many producers to many consumers directly to one another via a virtual marketplace	APPETIT IT-enabled platform for collaborative organisational arrangements TRL 4
• **Scottish farms and digital platforms**	Scotland	Small farmers and crofters	To promote and improve economic activities of small farmers and crofters	Developing a supportive environment for knowledge exchange and peer-to-peer learning on available digital tools to boost small farmers understanding the potential of digital technologies	Digital platform for training and collaboration, online social media, QR coding, 360-degree cameras and virtual reality demonstration TRL 3
• **Cloughjordan Food Hub**	Ireland	Local communities and small farmers	To shortening long supply chains and underpin a new food system owned and controlled by producers, eaters and local enterprises	Developing an online marketplace to facilitate small scale food producers and people in rural areas in accessing local markets, supporting local economies	Opensource digital platform TRL 7
• **Agrifood Technology**	Belgium	Arable crops	To reduce the use of crop protection products through site specific spraying	Detecting weed, disease and pest in commercial farms of arable crops	Ultra-high resolution RGB on drones and AI models, task map generation, label tools TRL 7

Living Lab	Country	Application scenario	Expected benefits	Problem solving	Technology (TRL)
• **Almeria Agroecology**	Spain, Almeria	Vegetable greenhouse production	To develop resilience in the local agricultural sector to create dignified employment and equitable distributed wealth	Facilitating interoperability of heterogeneous data from different sources	Sensors, actuators, centralised platform for data management TRL 5
• **Smart villages Network**	Slovenia	Vineyards sustainable agriculture	To increase sustainability and reduce the use of water and pesticides in vine production	Collecting different viticulture parameters and find the best IoT infrastructure for winemakers with different microclimate in the same vineyard.	IoT and data analytics, sensors, sever storing collected data, web platform, app for smartphone. TRL 7
• **Artificial Irrigation management system**	Slovakia	Vegetable greenhouse production	To improve the irrigation system in order to optimise the watering of plants in term of time and quantity	Providing irrigation doses for the plant according to the phenophase, water reserves in soil and meteorological situation	A mobile application based on new sensors for measure soil moisture placed at the depth where the decisive part of the active plant roots is located and model of the curve of physiological need for irrigation. TRL 7

Living Lab	Country	Application scenario	Expected benefits	Problem solving	Technology (TRL)
• **LIT Ouesterel**	France, Grand Ouest	Pig meat production	To find non-invasive practice methods and technologies to improve pig welfare and workers 'conditions, ease the farm management and traceability to reinforce food safety and quality control, from farmers to consumers	Facilitating data sharing between equipment and management software	Platform linking farm and equipment data TRL 6
• **Grassland product label**	Latvia	Grassfed beef cattle production	To improve the precarious market position of local beef cattle farmers	Providing an effective and easy-to-use marketing tool to promote an emerging food product from semi-natural grasslands characterised by high biodiversity	ZSA GEO map environment (https://app.smartagro.lv) TRL 7
• **Open Lab Sheep**	France, Occitanum	Dairy sheep farms	To prevent animal health and welfare problems in advance	Collecting automatically herd production data through tank weight measurement to	Digital milk counter and connected weight milk tank TRL 7
• **Occitanum Viti**	France, Occitanum	Vineyards sustainable agriculture	To manage fertilisation to preserve typicality of wines while protecting the environment	Modulating rate of applied fertilisers	Satellite images, vigour maps, user-friendly web interface TRL 7

Living Lab	Country	Application scenario	Expected benefits	Problem solving	Technology (TRL)
• **Spray drones**	Greece	Vineyards sustainable agriculture	To assess and analyse the best drone spraying configurations for field use and crop protection	Obtaining qualitative data on the spraying applications and droplet displacement, applying agrochemicals at a desired rate close to the canopy (commonly <5m).	Spraying UAVs (drones), GIS, sensors, IoT station, LiDAR for altitude adjustment, vision system, TRL 9
• **Automation of orchard management**	Czech Rep	Fruit crop production	To reduce impact of adverse weather on crops, reduce water and pesticide use, automation of irrigation and facilitate reporting obligations	Collecting, storing and analysing on farm data	A new sensor-based orchard management system for crop protection, remote control of the irrigation system, frost and pollination monitoring and an end-user application for the farmer. TRL 6
• **Agri-digital Building**	Germany	Knowledge transfer	To increase the application of digital and precision farming technologies in crop production	Supporting knowledge building on digitalisation in vocational education for prospective farmers and agricultural educators	Digitally related educational format TRL8
• **Grassland Management**	Estonia	Grassland	To improve monitoring of maintenance regimes of grasslands including both protected grassland and the cultivated ones managed for organic beef production	Capturing changes in vegetation/tree cover, support farmers with data in appropriate format	Drones, machine learning, web app TRL 3

Living Lab	Country	Application scenario	Expected benefits	Problem solving	Technology (TRL)
• **RAMAS**	North Macedonia	crop production	To improve agricultural professional support	Generating real-time field data that will be used by experts/advisors for delivering tailor-made advice	Farm accountancy form, field repository, user-friendly dashboard, earth observation data, environmental monitoring data. TRL5
• **Innovative Soil Scanner**	Hungary	arable crops	To optimise fertilisation and reduce environmental impact, through site specific fertilisers application	Analysing nutrients in soil in a fast, affordable, and reliable way	Soil scanner, NIR sensor, cloud, database, soil analysis, mobile phone, TRL9

Appendix 2. Economic costs and benefits of digitalisation

Table A2.1 – Economic Costs Taxonomy

Cost Typology	Cost Name	Description/Example	Sources
Operational/Operating Expenses (OPEX)	Maintenance and Repairs	Regular updates and maintenance of digital systems (hardware and software)	Telukdarie *et al.,* 2023; Ferrari et a., 2022
	Infrastructure Costs	Expenses for physical and technological support systems, such as the purchase, installation, and maintenance of an uninterruptible power supply (UPS) for backup power during outages	
	Licenses (subscription basis)	Subscription fees or periodic/regular payments for software licenses	
	Internal/external support	Internal support costs involve in-house resources for problem-solving, covering staff time, salaries, training, and tools, while external support costs are incurred for expertise from vendors or consultants, including service fees and contract charges	
	System Upgrading	Expenses for updating hardware like sensors and machinery, and software such as applications and systems, including purchase, installation, training, and potential downtime, aimed at enhancing performance, security, and features	Medel-Jiménez *et al.,* 2022
	Materials/Consumables	Costs for consumables that are essential for maintaining system functionality and efficiency	Medel-Jiménez *et al.,* 2022
	Electricity	Costs for powering the various technological devices, equipment, and systems	
	Usage	Ongoing costs for using digital marketing tools	Telukdarie *et al.,* 2023

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Cost Typology	Cost Name	Description/Example	Sources
	Disposal	Software disposal costs might include uninstallation, data migration, and potentially paying for professional services to ensure sensitive data is properly erased. For hardware, these costs could involve dismantling, recycling, or environmentally responsible disposal methods	
Investment/Capital Expenditures (CAPEX)	Infrastructure setup costs (Hardware)	Purchasing servers for data storage, as well as setting up the IT network, with costs varying based on the quantity and specifications of the devices	Telukdarie *et al.,* 2023; Fahmi and Savira, 2023; Medel-Jiménez *et al.,* 2022
	Infrastructure setup costs (Software)	Expenses for design, development, programming, integration, data migration, maintenance, and training, covering specialised programs and databases essential for system operation	Medel-Jiménez *et al.,* 2022
	Communication networks	Setting up and maintaining data communication systems, including backbone connectivity, regional networks, local sensor networks (LPWANs), network adaptors, database servers, network cards, and telephone or leased line rentals, to enable efficient data transfer/collection and analysis	Sadjadi and Fernández, 2023
	Licenses (one-time investment)	Legal permissions for using software or technologies, with terms defining usage rights, feature access, and updates	
	Internet access	The expenses incurred by individuals or businesses to connect to the internet, enabling them to access online resources, communicate, and utilise various digital services like weather forecasts, market prices, agricultural research, online marketplaces, and communication tools	Medel-Jiménez *et al.,* 2022

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Cost Typology	Cost Name	Description/Example	Sources
	Development	Designing precision agriculture tools, creating automated irrigation systems, or crafting data collection and analysis platforms. The cost of development includes expenses associated with hiring software developers, engineers, and other experts, as well as procuring necessary hardware components and software licenses	Subach and Shmeleva, 2022, Valiyev *et al.,* 2022; Bekaroo *et al.,* 2016
	Technology (equipment)	Investments in precision farming tools, sensor networks, data analytics platforms, and automation systems	Brahmanand and Singh, 2022; Ferrari et a., 2022; Medel-Jiménez *et al.,* 2022
Transition	Training and Learning Costs/ Digital Skills Development	Both initial and ex-post training employees to use Enterprise Resource Planning (ERP) systems	Telukdarie *et al.,* 2023; Medel-Jiménez *et al.,* 2022; Ferrari et a., 2022
	Learning Opportunity Costs	Opportunity cost arises from employees attending training for new software or hardware, temporarily diverting them from regular tasks and reducing productivity	Medel-Jiménez *et al.,* 2022
	Business Process Re-engineering (BPR) cost	Streamlining processes to fit digital tools	
	System Customisation	Customising CRM systems to company needs	Telukdarie *et al.,* 2023
	Standardisation	Upgrading to industry-standard hardware and software can incur expenses for replacement, user training, and potentially higher costs for non-standardised hardware	
	Data Pre-processing	Data pre-processing, also known as data cleaning, is a fundamental step in data analysis. It involves identifying and correcting errors, handling missing data, and unifying data structures to ensure the dataset's quality and reliability	

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Cost Typology	Cost Name	Description/Example	Sources
	Data Reconciliation	Aligning and comparing data from various sources for accuracy, it detects and rectifies discrepancies, enhancing data reliability for informed decisions	
	Data Mining	Extracting valuable insights from complex agricultural datasets, revealing trends, relationships, and correlations for informed decisions and precision agriculture	
	Site-specific data collection	Soil sampling and NDVI mapping	
Switching	Learning Curve	The learning phase in adopting new technology when employees become proficient, potentially causing temporary productivity slowdowns and reduced output	Balasundram *et al.,* 2023; Medel-Jiménez *et al.,* 2022
	Specialised third-party	External cost arising when an organisation hires specialised third-party services instead of maintaining in-house expertise, providing flexibility without training costs	Sadjadi and Fernández, 2023
	Data conversion	Costs linked to migrating data when transitioning to new systems or formats. Components involve data migration, mapping, validation, cleansing, testing, and user training	
	Advanced Monitoring	Costs of specialised hardware and software for centralised monitoring systems, including initial investments and ongoing expenses like maintenance, data management, and skilled personnel	
Transaction	Labor external cost	Hiring IT consultants for cloud computing integration	

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Cost Typology	Cost Name	Description/Example	Sources
	Data dominance disparity	Disputes over data ownership, profits, and access control among stakeholders	Sadjadi and Fernández, 2023; Sadjadi and Fernández, 2023
	Risk of surveillance, discrimination and bias	Data exchange cost pertains to establishing equitable data sharing among value chain participants, ensuring value addition and fair benefit distribution	Sadjadi and Fernández, 2023
	Privacy and security	Data governance costs are linked to managing, securing, and ensuring privacy in digital agriculture, vital for protecting farmer privacy and regulatory compliance	
	Data sharing	Missed benefits from not sharing data due to privacy, security, or control concerns, affecting collaboration and innovation	
	Data Colonialism	Imbalance of power when one group or region extracts data without consent or benefit to the originators, benefiting more powerful entities	
Risk Management Costs	Development risks	Potential loss from unproven digital initiatives	Telukdarie *et al.,* 2023;
	Implementation risks	Exceeding budget on new software deployment	Telukdarie *et al.,* 2023;
	Technological risks	Investing in AI without guaranteed ROI	Telukdarie *et al.,* 2023;

Table A2.2 – Economic Benefits Taxonomy

Benefit Typology	Outcome Benefit	Description/Example	Sources
Operational Efficiency	Enhanced Agricultural Efficiency	Moocall Breed Manager, iLivestock, and Farmwizard Beef Manager are digital tools for livestock management. Moocall helps track breeding and calving data, iLivestock provides	Attaran and Celik, 2023; Balasundram *et al.,* 2023; Sadjadi and Fernández,

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

Benefit Typology	Outcome Benefit	Description/Example	Sources
		comprehensive animal records, and Farmwizard records herd health and offers cloud-based storage for data management	2023; Ferrari *et al.,* 2022
	Increase productivity	Digital tools enhance crop yield via drone-assisted soil analysis. Drones provide insights into soil chemistry, optimising harvest by ensuring essential elements for efficient plant growth. Utilising optical sensors addresses key agricultural challenges by fine-tuning fertiliser application and minimising wastage	Costa *et al.,* 2023; Brahmanand and Singh, 2022; Maffezzoli *et al.,* 2022b; Shao *et al.,* 2022
	Cost Reduction	Adopting digital technology in agriculture allows for more efficient cotton management with fewer managers, using remote sensing drones and IoT tools for field scouting, which saves an average of 1184.25 CNY/ha over manual methods	Balasundram *et al.,* 2023; Duncan *et al.,* 2022
	Optimised Agricultural Logistics	Standardising data formats in German wood supply chains cut the time from harvest to accounting by 28%, improving efficiency, safety, and customer service in wood supply practices. Guidance systems and controlled traffic farming reduce operational overlaps, cutting down on input and fuel use without compromising production levels	Moore *et al.,* 2022; Maffezzoli *et al.,* 2022b
	Enhanced Substitution Strategies	Digital technologies facilitate replacing harmful practices with eco-friendly alternatives, such as using weeding robots instead of herbicides, maintaining production while reducing environmental and health impacts	Izuogu *et al.,* 2023
	Improved Post-Harvest Management	Digitalisation reduces post-harvest losses in agriculture by improving access to value addition facilities	Finger, 2023
	Search Optimisation	Reduce the time spent searching for and purchasing materials, equipment, and services, marketing manufactured products	Sadjadi and Fernández, 2023; Chaudhary and Suri, 2022;
	Transaction Optimisation	eNAM demonstrates lower transaction costs compared to offline trade, benefiting sellers by securing better net prices and facilitating cost reduction efforts	Chaudhary and Suri, 2022; Duncan *et al.,* 2022; Maffezzoli, 2022a
Enhanced Decision	Data-Driven Sales	Digital twin technologies enhance sales strategies by using GPS for precise tracking and Big Data	Fahmi and Savira, 2023; Sadjadi and

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

Benefit Typology	Outcome Benefit	Description/Example	Sources
Making	Optimisation and Customer Intelligence	Analytics (BDA) for insights on sales performance, travel, and fuel use. Handheld terminals collect real-time data, aiding in accurate supply chain planning. BDA also analyses diverse data sources to understand consumer behaviors and trends, improving customer understanding and confidence through digitalisation	Fernández, 2023; Telukdarie *et al.,* 2023
	Data-Driven Efficiency	Biometric sensors enable real-time monitoring of animal health and behavior, using both non-invasive and invasive methods. Farmers use these sensors to collect and analyse data for population-level insights. Advanced statistical algorithms and big data systems process and integrate this data, offering trend patterns and decision-making tools	Maffezzoli *et al.,* 2022b
	Accelerated Problem Solving and Innovation	IoT technologies in agriculture enable predictive maintenance, improve machine efficiency, extend equipment lifespan, and facilitate redesign for enhanced capabilities, including product and service optimisation. Benefits also include cloud computing and AI integration for lifecycle monitoring, defect detection, increased satisfaction, and food safety enhancements. Additionally, IoT supports precise crop tracking through accurate data accumulation over time	Fahmi and Savira, 2023
	Enhanced Data Quality and Utilisation	Digital technologies allow for precise information gathering and storage, while advanced information technology supports more sophisticated data processing, behavioral algorithm development, and predictive model creation. This is particularly relevant in supply management, where harvester data is more crucial than that of operational managers	Forbs, 2017; Costa *et al.,* 2023; Chaudhary and Suri, 2022; Subach and Shmeleva, 2022; Labelle and Kemmerer, 2022; Sadjadi and Fernández, 2023; Valiyev *et al.,* 2022; Duncan *et al.,* 2022
Business and Economic Growth	Increased Competitiveness	Cloud solutions empower farmers with resources to compete with larger firms, enhance investment returns, and quickly adapt to customer-centric models for improved competitiveness and faster product launches	Sadjadi and Fernández, 2023; Brahmanand and Singh, 2022; Medel-Jiménez *et al.,* 2022
Economic Growth and Livelihood	Enhanced Selling Price	Openness and transparency in e-platforms enhance sellers' bargaining power, connecting them with more buyers and enabling farmers to	Sadjadi and Fernández, 2023; Maffezzoli *et al.,*

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Benefit Typology	Outcome Benefit	Description/Example	Sources
Enhancement		achieve better prices, reducing dependency on local agents and protecting against price manipulation with strong yield data supporting higher valuations	2022b
	Enhanced Production, Quality, and Revenue	Digital Twin technology enhances the farm supply chain with full visibility, food quality assurance, and improved collaboration. It enables real-time farm monitoring and virtual updates, optimising soil, increasing yields, and producing healthier products. Industry 4.0's adoption could lead to a 15% increase in gross value added, with wireless sensors providing real-time data for improved forest management and ICT applications enhancing value in harvest planning and timber sales	Balasundram *et al.,* 2023; Costa *et al.,* 2023; Abdulai, 2022; Bareyko *et al.,* 2022; Labelle and Kemmerer, 2022; Müller et al. (2019)
	Enhanced Revenues (through SFSC)	Platforms enable direct links between producers and consumers, reducing intermediaries	Labelle and Kemmerer, 2022
	Enhanced Access to Agricultural Funding Opportunities	Crowdfunding platforms help farmers obtain costly equipment like tractors and irrigation systems, providing innovative lending solutions for better financial management and profit optimisation. Mobile banking enhances these efforts with easy transactions and economic management in agriculture	Sadjadi and Fernández, 2023; Abdulai, 2022; Medel-Jiménez *et al.,* 2022; Shao *et al.,* 2022
Financial Well-being Enhancement	Income Preservation and Opportunity Maximisation	Agriculture's digitalisation safeguards income by mitigating losses and optimising opportunities. This preserves financial potential, ensuring economic stability and security for farmers and agribusinesses	Medel-Jiménez *et al.,* 2022; Colaço and Bramley (2018)
Enhanced Food Standards	Enhanced Product Quality	Adopting intelligent techniques reduces crop management costs, making specific crops more economical and boosting sales and revenues through strategic selection	Finger, 2023; Shah and Razaq, 2020; Kim et al. (2018)
Trade and Market Development	Enhanced Market Access and Information	Digitalising the procurement phase in agriculture, similar to e-commerce, benefits farmers by providing transparent feed movement tracking, saving time, and enabling better monitoring of animal welfare. Blockchain with sensor integration ensures safe, eco-friendly, traceable food production. Wholesale e-trading platforms enhance transparency and demand for produce, driving	Sadjadi and Fernández, 2023; Scholz *et al.,* (2018)

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Benefit Typology	Outcome Benefit	Description/Example	Sources
		solutions for improved food production and communication between consumers and farmers	
	Enhanced Global Market Integration	Facilitates market connections among various stakeholders in the value chain, including small farmers, cooperatives, input providers, service entities, processors, buyers, and exporters	Gavrilova, 2022
Innovation and collaboration	Catalyse Innovative Digital Ecosystems	Facilitates dynamic interactions within supply-chains and business communities, collaboratively crafting value propositions tailored to specific customer needs and aspirations. Digital tools spark innovation, driving the emergence of startups and enterprises that harness technology to reshape agricultural practices and markets	Ayamaga *et al.,* 2023; Balasundram *et al.,* 2023; Finger, 2023; Sadjadi and Fernández, 2023; Goff, 2019

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

Appendix 3. Overview of definitions

Table A3 – Overview of definitions

Concept	Definition
Actor-centred system approach	An approach that looks at the different needs, motivations and behaviour between actors in a systemic context
AKIS	Agricultural Knowledge and Innovation Systems: the set of actors and activities involved in the production of knowledge in agriculture
Activities	Set of actions, interactions, behaviour, communication that can influence a system. They are regulated by rules generated by governance systems
Actors	Individuals, roles, groups, stakeholders interacting in the system
Actuation	The action that executes the decisions made according to the sensing followed by an intelligence process that result in instructions
Application Scenario	A field of application of digital technologies in given contexts (example irrigation in arid contexts)
Artifacts	The set of human made products, capital and technologies
Business processes	Process of integrating digital technology, including hardware, software and communication components, into established agricultural processes
Capabilities	The individual/organisational know-how/abilities to achieve the intended goal, which implies a combination of resources and organisational routines or guidelines
Co-benefit	Effects of an activity or investment that meet simultaneously the interests of multiple stakeholders
Conduciveness	The capacity of a digital ecosystem to reduce the transaction costs related to adoption of digital technologies
Contextual factors	Include entities, relationships and activities that that intervene in the system
Conversion factors	The conditions of the context that generate actors' capabilities
Demo Farm	A farm where a digital technology is demonstrated for learning purposes
Demo Technology	A technological application chosen for demonstration in a demo farm

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Concept	Definition
Digital ecosystem	An organised set of digital, social-economic, organisational, and physical components that support the production, storage, communication, and use of digital technologies and data
Digital intelligence	The process of transforming data with specific signification into information
Digitalisation	The process of socio-economic-ecological-technical change related to digitisation
Digitisation	The process of turning analogic processes into digital processes
Digitised socio-physical system	It refers to the system in which living laboratories are brought after the demonstration of technology at farm level
Driver (External)	Driving components of an ecosystem that can be classified into social/cultural, technical/technological, economic/financial, environmental and political factors
Driver (Internal)	Driving components of a user that can be classified into capabilities, opportunities and motivation factors
Digital readiness of farmers	The "individual or organisation's ability to adapt and effectively utilise digital technologies and tools in order to achieve their goals and objectives". The farmer digital readiness encompasses a range of skills, knowledge, capabilities, and resources necessary to effectively navigate and leverage digital tools and technologies
Digital ecosystem conduciveness	Extent to which the context supports the growth and success of digital activities, such as the development of new technologies, the creation of new businesses, and the adoption of digital solutions…"
Focal action situation	A situation where components of a socio-ecological systems interact to provide an outcome
Governance systems	Rule structures that establish how decisions are taken, i.e. constitutional rules, contractual arrangements, accountability systems, strategic exercises, traditions and routines
Living Lab	A network of farmers, knowledge intermediaries, stakeholders, policy makers constituted around an emerging problem
Macro-level social disaggregation	Pathways that can lead to low equity and social inclusion on a global level as digitalisation increases, leaving countries and regions behind
Macro-level social integration	Pathways that can increase equity and social inclusion through digitisation of the agri-food sector
Micro-level social disaggregation	Pathways that can lead to low equity and social inclusion on a local level as digitalisation increases, leaving communities and sections of the population behind

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Concept	Definition
Micro-level social integration	Pathways that can increase skills and capabilities at the core of social integration, self-efficacy and effective skills to use digital technology in the agri-food sector
Natural resources	Ecosystem components extracted to be implemented in our anthropic system
Operation costs	The costs related to inputs necessary to operate a digital technology
Process modelling	A representation of how digital technologies work in a socio-technical-ecological context
Rules	The set of institutional factors such as norms, regulations, decision-making, governance systems and policy formulation
Scaling readiness	The potential of a digital technology to be adopted by large numbers of farms in different contexts. Refers to an action-oriented evaluation support is designed to address emerging and unpredictable change processes
Science-Policy interface	Organised interaction between researchers, stakeholders and policymakers to provide actionable knowledge related to relevant policy issues
Sensing	The use of sensors in precision agriculture and provides the opportunities to gain large amounts of relatively inexpensive information
Socio – physical System	This represents the starting point system with no digitisation
Socio-cyber-physical system	System in which the technical and social aspects overlap, and within them a cyber-physical system overlaps with a socio-technical one; this allows one to understand the relationship between digital technologies and the context in which they are embedded
Socio-ecological system	A system in which social and ecological components affect each other
Socio-technical system	Refers to the hybridity of the situations that characterise social and economic aspects of life, and the reciprocal influence between human and non-human components
Socio-technical system approach	Linear approach systems to improve comprehension of costs and benefits on how digitisation can strengthen digital transformation towards sustainable and ethical digitisation
Sustainable digitalisation	A process that links digital and ecological transitions together in a socio-ecological-technical transformation contributing to Sustainable Development Goals
System dynamics	Non-linear processes occurring in a system

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Concept	Definition
System readiness	Refers to the capability of a system to achieve a given goal through a process given by the interaction between the User readiness and the Scaling readiness
Systemic costs	The costs generated by the indirect, retarded, impact of digital technologies on the socio-ecological-technical system in which the process is embedded
Transaction costs	The costs related to the search, setup, adaptation, negotiation necessary for adoption of digital technologies
Transformative change	Change that affects the structural components of a system
Transformative policies	Policies that address the root causes of emerging problems and give direction to change. They have three characteristics: directionality, reflexivity, market integration
Transition	Process that through digitisation enables the change of level from a starting state to digitised outcomes
Transition costs	The costs necessary to turn analogic processes into digital
Transitioned socio-cyber-physical system	System resulting from digitalisation at the farm level, which implies that natural and digital ecosystems, governance systems, resource units and actors are interrelated in a non-linear way, leading to a system transition
Use case	A specific case in which the application of digital technologies is studied
User readiness	Ability to use the technology in a meaningful way, determined by capabilities, motivation and opportunities

Co-funded by the European Union

CODECS has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101060179. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.