TITAN

Transparency solutions for transforming the food system

Deliverable 3.4 – 1st version of the approach for overcoming cross-cutting challenges

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Authors	Esra Zorer, Siu-Lie Tan, Dr. Marcela Tuler de Oliveira, Prof. Dr. Marijn Janssen (Delft University of Technology)
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Executive Summary

Food supply chains (FSCs) have been struggling to ensure the safety, sustainability, and health of food products due to the lack of communication and the difficulty of sustaining control over global and complex networks. This situation requires the integration of digital technologies to improve the information flow within FSCs and enhance transparency to reduce the risk of aforementioned issues. However, FSCs are highly fragmented in relation to the type of food products, the size of operations, the actors involved, the geographic locations, etc. Therefore, each FSC operates in a unique context that makes choosing a suitable technology solution complicated, as it depends on the context, which may be shaped by the stakeholders, processes, infrastructure, external influences, and so on. Additionally, each digital technology option has its own benefits and trade-offs, and usually, it is a mix of technology that would enhance transparency in FSCs, with each technology solution addressing a specific issue while complementing each other.

This deliverable is connected to T3.3: Develop and evaluate approaches for overcoming cross-cutting challenges, and it provides the first version of the approach with possible considerations. In this first version, the focus is put on FSC steps in relation to the stakeholder element of the context to bring more structure to the discussion. The steps were identified in relation to the D2.1 report created by WP2 of the TITAN project, and these steps are, namely, primary production, processing, transportation, distribution, and retail. Accordingly, various requirements and challenges are identified in the context of each FSC step. Then, different technology solutions are provided for the requirements and challenges to lay the foundation for creating a mix of technology options.

The content of this document is based on the literature without focusing on a specific FSC context, and the goal is to present the way of approaching the complexity of transparency creation. After this step, the approach will be applied to the specific context of the selected TITAN pilots, and the approach will be improved through iterative sessions with the pilots. A case study will be created for each pilot, and the outcomes will be used to develop a framework for transparency creation through digital technologies as the final version of the approach.

Authors and Reviewers

Main Responsible		
Organization	**Name**	**Mail**
Delft University of Technology	Marijn Janssen	m.f.w.h.a.janssen@tudelft.nl
Author(s) / Contributor (s)		
Organization	**Name**	**Mail**
Delft University of Technology	Esra Zorer	e.zorer@tudelft.nl
Delft University of Technology	Marijn Janssen	m.f.w.h.a.janssen@tudelft.nl
Delft University of Technology	Siu Lie Tan	f.s.tan@tudelft.nl
Delft University of Technology	Marcela Tuler de Oliveira	m.tulerdeoliveira@tudelft.nl
Reviewer(s)		
Organization	**Name**	**Mail**
INRAE	Bernadette Durrand	bernadette.durand@inrae.fr

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Table of Contents

Introduction 5

Objectives of the document 6

Associated Tasks 6

How to read this document 6

1. Background 7

2. Stakeholders as an Element of the Approach 8

2.1 Food Supply Chain Steps 9

2.1.1 Primary Production 10

Connections Between Requirements, Challenges, and Technology Solutions 10

2.1.2 Processing 18

Connections Between Requirements, Challenges, and Technology Solutions 19

2.1.3 Transportation 26

Connections Between Requirements, Challenges, and Technology Solutions 26

2.1.4 Distribution 32

Connections Between Requirements, Challenges, and Technology Solutions 33

2.1.5 Retail 39

Connections Between Requirements, Challenges, and Technology Solutions 39

3. Conclusion 46

3.1 Future Steps 47

4. References 47

List of Tables 81

Appendix 81

Introduction

The European Green Deal is the central strategy of the European Union to transform European society with a modern, resource-efficient and competitive economy while addressing climate and environmental challenges. The Farm to Fork strategy follows the path traced by the European Green Deal while responding to increased public awareness and the growing demand for a Food System capable of providing healthy, sustainable and affordable food. All players in the Food Value Chain are called upon to contribute to this goal thanks to recent technologies and recent discoveries in the sector. Farm to Fork aims to set a global standard that can overturn the current paradigm consisting of air, water and soil pollution, loss of biodiversity, climate change, and excessive consumption of natural resources.

For such an agrifood system to flourish, consumers must have better access to healthy, sustainable and affordable food, with transparent information about the integrity and true value of food, so that they can make the better food choices that are necessary to increase demand. Enhancing transparency is an essential element in achieving this goal. Without transparent (and preferably immutable) proof, sustainability claims run the risk of becoming hollow marketing phrases instead of useful information that all the actors in the value chain (producers, sellers, consumers) can use to make choices that align with their values.

TITAN intends to leverage transparency and digital innovations in the food sector to pursue this paradigm shift: transforming the food system into a demand-driven economy that provides consumers with healthy and sustainable food. To achieve this goal, TITAN will provide a broad platform for the development of pre-identified technologies and pilots that will be selected during the project through an open call for proposals, also by facilitating the involvement of primary and secondary stakeholders in this process, analysing current policy to set up a set of recommendations and finally setting up an inventory to identify current digital innovations and future challenges.

As one of the work packages of TITAN, *WP3 – Digital technologies* aims to create an inventory of technologies and validated approaches to overcome cross-cutting challenges for transparency. This deliverable contributes to the aims of WP3 by providing an approach to overcome cross-cutting challenges for transparency in food supply chains through digital technologies. The approach is developed based on the outcomes of previous publications of WP3 (D3.1 – Requirements and cross-cutting challenges for transparency and M3.7 – Technology scan review). The approach provided in this document represents the first version, and it will be further improved in the coming years until the end of the TITAN project.

Objectives of the document

This document represents the first attempt to develop an approach to building connections between existing digital technology solutions to create transparency in FSCs and the requirements and cross-cutting challenges identified in different contexts. As creating transparency in a FSC is easier said than done, this approach aims to introduce a more structured method to evaluate the context and develop possible directions to create transparency. The report includes findings from the previous WP3 and WP2 publications and benefits from the literature to provide a broad view of possible considerations.

Associated Tasks

This deliverable report builds up on the previous findings of WP3, and it is linked to T3.1 – Requirements on digital technologies and methodologies for creating transparency in the food supply chain and associated cross-cutting technological challenges, T3.2 – Create an inventory of state-of-the-art technologies and methodologies for opening data and transparency and T3.3 – Develop and evaluate approaches for overcoming cross-cutting challenges. It also incorporates the findings of WP2 in connection with D2.1 – Preliminary identification of stakeholders and their roles for transparency.

How to read this document

As this document presents the first version of the approach, it includes possible requirements and challenges that could be relevant in different contexts. These possible requirements and challenges are based on previous findings and literature; however, it is recommended to focus on the approach rather than the content. To develop a more comprehensive understanding, it is recommended to also read D3.1 – Requirements and cross-cutting challenges for transparency, which was released on M14 and D3.6 – Approaches for overcoming cross-cutting challenges that will be delivered on M48.

1. Background

Food supply chains (FSCs) have been facing several issues that require immediate attention, and there is a growing consensus on the key role of transparency across FSCs, both in the literature and practice. The vast amount of case studies on enhancing transparency in FSCs (differing in type, size, and location) demonstrates significant evidence for the potential improvements in these issues, such as food safety, sustainability, and health(Cocco et al., 2021; Kittipanya-ngam & Tan, 2020; Tsolakis et al., 2023). Today, the complexity and interconnectedness of global FSCs make it necessary to involve the use of digital technologies to create transparency among stakeholders (Manning, 2018). In this regard, the increasing know-how and innovation have led to the emergence of various tools that can be used for different purposes in relation to their unique features[1]. Each of these technologies has its own potential benefits and limitations in relation to creating transparency. According to the results of the research activities carried out so far by WP3 within the TITAN project, it is evident that focusing on technology options alone is not sufficient to ensure a robust approach to creating transparent FSCs.

Compared to other sectors, the food sector is highly fragmented, with a multitude of small and medium-sized enterprises (SMEs) alongside large multinational corporations. The type of FSCs is highly differentiated, with a wide variety from fresh produce and livestock to processed foods and beverages. The food sector is also highly regulated with a focus on food safety and health, and these regulations are frequently updated (Mol, 2015). In connection, understanding the unique characteristics of the food sector, as well as the context of each FSC, is of great importance (Bastian & Zentes, 2013). However, defining the context of a system is not an easy task, and there are varying approaches in the literature regarding what it comprises. Fundamentally, the context of a FSC can be linked to several elements, such as FSC stakeholders, processes, infrastructure, and external influences (economic, environmental, technological, social, legal, and political factors) (Schäfer, 2023). These key factors may shape how transparency can be created in an FSC regarding the relevant requirements and cross-cutting challenges.

As previously described in D3.1, requirements refer to the specific criteria, standards, conditions, set of rules, or guidelines that must be met or followed to ensure transparency. They could include compliance with regulatory mandates, industry standards, best practices, and voluntary commitments and encompass various aspects of data sharing, documentation, and communication practices to establish transparent FSCs. Requirements are often specific to the operations, detailing what the system must do, and they are defined by the goals and objectives of the transparency initiative. Some

[1] The list of technologies is provided in D3.1 and M3.7.

examples of requirements would be data accuracy, interoperability, data security, or regulatory compliance. On the other hand, cross-cutting challenges are broader issues or obstacles that affect the implementation of transparency efforts. Some examples of cross-cutting challenges could be resistance to change, trust, collaboration, confidentiality, technology adoption, or scalability. In this regard, cross-cutting challenges are more strategic, focusing on the broader issues that can impact the overall success of the system. Understanding the requirements and cross-cutting challenges allows us to develop a better approach to achieve transparency by addressing specific functionalities and broader issues that might hinder progress. However, in some cases, there might be some overlap between the two concepts. For instance, a requirement identified in one context could be considered a challenge in another context if there is an inability to meet the requirement. Similarly, overcoming a cross-cutting challenge could be identified as a necessity for a specific solution to achieve transparency in that context, which would turn it into a requirement. These considerations indicate that both the requirements and cross-cutting challenges are shaped by the context and, therefore, are context-dependent.

The main reason for considering requirements and cross-cutting challenges when formulating an approach to achieve transparent FSCs is rooted in the need for clear, structured, and actionable framing of the situation. When the necessary capabilities of a system and the obstacles in achieving those capabilities are well-defined, there could be progress towards building meaningful connections between the elements of the system that would lead to solutions. However, enhancing and maintaining transparency in FSCs requires a closer examination of the context of the transparency initiatives. Here, it is essential to imagine how transparency could be achieved in an FSC, which invites us to discuss the actions that can be taken in different steps of FSCs. These actions are linked to the identification of the relevant requirements and cross-cutting challenges with suitable technologies and methods to meet those requirements and overcome cross-cutting challenges. This document dives deeper into the context of creating transparency in FSCs through the key considerations of the steps of FSCs and building connections to digital technologies.

2. Stakeholders as an Element of the Approach

When imagining an approach that connects digital technologies to the context in which they would fit appropriately, the context needs to be examined by focusing on its specific elements. As previously mentioned, stakeholders are one of the main elements that shape the context, and in this first version of the approach, we will focus on the stakeholders that would employ digital technologies in different FSC steps to enhance transparency. Here, the main goal is to discuss the possibility of exploring different contexts in relation to differing conditions of FSC steps and whether it affects the choice of

technology. For this, the primary stakeholders identified in D2.1 are taken as the basis for the discussion and connections with the literature are made for possible technology solutions in relation to the requirements and challenges identified in different contexts.

2.1 Food Supply Chain Steps

It is not possible to imagine an FSC without the steps in the journey of the food products, where each step consists of FSC actors executing their tasks to ensure uninterrupted material flow. Transparency occurs in an FSC when the information flows between these steps, and the creation of transparency is affected by the unique tasks carried out in each step (Islam, Cullen, et al., 2021). The type of data collected, stored, shared, and received in each step might be different, as well as the tools needed for these actions (Mangla et al., 2021). Therefore, looking closer at the context of each FSC step would bring more clarity to the information for transparency creation through digital technologies. The actors operating in each step have specific goals connected to their activities, and they pursue transparency to achieve these goals. The requirements identified on each FSC step serve to enable transparency for these goals, and recommendations on technology options are included to overcome challenges linked to these requirements. Overall, the approach to create transparency in FSCs needs to be rooted in the connections that can be built between the requirements, their importance in the context, relevant challenges, and possible technology solutions.

FSCs have different structures regarding which steps would be included in the material flow, depending on the type, size, and location of the FSC (Bastian & Zentes, 2013). For this reason, there are varying approaches in the literature regarding the steps of an FSC. From a broad perspective, this doesn't carry much weight, as the inclusion/exclusion of the steps would become relevant when discussing the context of a specific FSC. Nonetheless, this report provides a discussion from a general point of view to develop a structured approach, and it does so by referring to the primary netchain stakeholders listed in the D2.1 report (Section 5), which are input providers, primary producers, processors, transportation, distribution, retail, and consumers[2]. In the report, input providers are mentioned only a few times, and their relevance is mostly linked to providing goods and services to the stakeholders in primary production. Even though they are increasingly engaged in the provision of information services, as stated in D2.1, they are not included in this first version of the approach for the sake of simplicity. Another consideration here is linked to the involvement of the consumers in the approach. According to D2.1, consumers can influence transparency creation in FSCs through their buying decisions and the pressure they can apply on policymakers. However, the report also mentions

[2] See D2.1 - Preliminary identification of stakeholders and their roles for transparency.

that they do not possess any transparency information themselves. Therefore, their perspective will be discussed in the context of the retail step, as it is often the step with direct interactions with the consumers. To sum up, the FSC steps included in the approach are primary production, processing, transportation, distribution, and retail. The following section discusses possible requirements and challenges that can be identified in relation to transparency creation and provides suitable technology solutions based on the literature.

2.1.1 Primary Production

D2.1 report states that primary production is the focus of many FSCs, and it also plays a critical role in transparency initiatives. This step is where raw food materials are produced, and depending on the FSC type, this production could be based on agriculture, livestock farming, aquaculture, fishing, and so on. The main actors in this step would be farmers, agricultural producers, crop growers, livestock farmers, and fishers. According to the D2.1 report, producer cooperatives can also be included in this step as the natural extension of primary production due to the potential role they can play in transparency creation. The main activities taking place in this step have a wide range, including land preparation, planting, cultivation, harvesting, catching, breeding, storing, and transporting. D2.1 report highlights that what happens in primary production is mostly known by the producers, which makes them potential gatekeepers of transparency. As a result, other stakeholders (such as retailers and processors) are interested in having access to this information, yet engaging the producers with transparency initiatives is identified as a complicated task. Regardless, ensuring food safety and quality, productivity, profitability, and sustainability appears to be of high importance in this step, and transparency initiatives can play a key role in achieving these goals (Li et al., 2014; Mangla et al., 2018).

Connections Between Requirements, Challenges, and Technology Solutions

Requirement 1: Detailed Record-Keeping

Accurate and detailed records are crucial for achieving productive, profitable, and sustainable operations, as they can improve accountability, quality control, regulatory compliance, and market access (Kosior, 2018). If farmers are taken as an example, they might keep records of farm inputs and outputs (seeds, fertilisers, pesticides, other inputs, and harvest) and log activities, such as planting dates, irrigation schedules, and pest control measures. In order for these records to result in transparency, they should be managed efficiently. However, manual data entry still seems to be the common method, especially in the case of small-scale farmers in developing areas (Bachev, 2012; Bhat et al., 2022). In connection with this, the lack of digital literacy, resistance to change, and lack of time are considered some of the main factors that lead to manual data entry (Friedman et al., 2024). In the case of small farmers living in rural areas, resource constraints regarding the costs and infrastructure

can also hinder the adoption of digital record-keeping tools. Additionally, the variability of farming practices in connection with the diverse farming methods and scales can make it difficult to keep efficient records, requiring flexible solutions (Emmi et al., 2023).

Among the potential technology solutions, mobile and web applications with simple and intuitive designs could cater for the specific needs of farmers with customisable templates for digital record-keeping (van Greunen, 2020). This would reduce the threshold for resistance to change and required digital skills, but it does not influence the data quality. Ensuring accurate and detailed records is strongly linked to successfully collecting and logging vast amounts of farm data (Wolfert et al., 2017). In relation, benefiting from automated data collection tools (IoT devices, drones, and satellites) would reduce the workload and complexity for the farmers as these tools could collect and analyse data for record-keeping (Wolfert et al., 2017). Furthermore, considering viable storage solutions is also an important factor in ensuring the long-term accessibility and security of the records. To secure the data while enabling easy access, cloud-based platforms could be a suitable solution as they can integrate with other digital tools and do not require high digital literacy or investment to adopt (Dineva & Atanasova, 2022). In the case of having sufficient financial resources and technical skills, blockchain technology (BCT) could be a promising solution for ensuring the accuracy and security of records (Musah et al., 2019).

Requirement 2: Real-Time Monitoring and Reporting

Continuous and real-time monitoring and reporting are essential for the primary production step operations in relation to making timely and informed decisions, precise and efficient use of resources, and ensuring sustainability (Astill et al., 2019). For farming and agriculture, it could vary from monitoring the environmental conditions (soil moisture, temperature, and weather conditions) to crop health (growth, pest infestations, and disease outbreaks) (Kingra et al., 2016). In the case of livestock farming, the monitoring activities can collect data on animal health, resource use, production performance, and environmental impacts (Pardo et al., 2022). Monitoring activities in fishing can involve collecting data on fish populations, catch volumes, species composition, gear use, fishing time, and environmental conditions (Van Helmond, 2022). Achieving these would require integrating digital technologies as it involves collecting, storing, and managing vast amounts of data.

The actors operating in this step often have limited access to and familiarity with advanced monitoring technologies, which is especially a problem in small-scale operations in remote or rural developing areas as it would also bring challenges due to infrastructure limitations (Bachev, 2012). The actors could also experience data management issues in connection with the high volume of real-time data and ensure the security of sensitive data (Kaur et al., 2022). For managing the data collection process,

integrating cost-effective IoT sensors that are connected to a cloud-based system for data aggregation and analysis might be a suitable solution in this context (Debauche et al., 2022). Data from drones and satellites could also be integrated for crop monitoring, field mapping, and historical data analysis (Z. Zhang & Zhu, 2023). Here, it is critical to consider the potential security breaches in IoT devices through cyber-attacks and in order to reduce this risk, actors in this step could apply various measures like encryption, authentication, regular firmware updates, and network security through deploying firewalls and intrusion detection/prevention systems (Mahlous, 2024). As an emerging technology, TinyML shows promise in risk reduction as it can be used to detect anomalies in sensor data, which may indicate potential cyber-attacks (Tsoukas et al., 2022).

Securely storing such vast amounts of data is another concern that could be addressed by varying technology solutions. Cloud storage solutions are highly popular in this regard, and they also provide built-in security features (Debauche et al., 2022). In case storing all of the data on the cloud could be too costly for some actors, hybrid storage solutions that combine local and cloud storage would be more suitable. To store data at scale, data lakes appear as a viable option which also facilitates advanced analytics and machine learning (Debauche et al., 2022). To reduce the amount of data that is worth storing, edge computing could be used to process data near the source and filter only relevant data to send to storage (Yu et al., 2024). Another solution could be blockchain technology (BCT) to securely store critical data while using another data storage solution for less critical data (Lin et al., 2020). Since real-time data is collected to support decision-making and timely response, it is also important to consider technology solutions for data visualisation and analysis (Spandana & Pabboju, 2023). In relation, mobile applications and dashboards can visualise real-time data collected from sensors and send alerts and notifications (Spandana & Pabboju, 2023). At a more advanced level, artificial intelligence (AI) and machine learning (ML) tools could be used for predictive analysis for strategic planning and anomaly detection for early intervention (Tsolakis et al., 2023).

Requirement 3: Traceability Mechanisms

Building systems to trace and track the movement of food products through the whole FSC is considered essential by policymakers, industry actors, and academia for creating transparency. Traceability mechanisms have the potential to build consumer trust, provide quality assurance, have better recall responses to food safety incidents, reduce the risk of fraudulent behaviour, and improve market access (as many retailers and regulatory bodies require traceability for products) (Garaus & Treiblmaier, 2021; Kechagias et al., 2023). In order to trace and track the movement, FSC actors need to create unique identifiers for batches of food products to facilitate recalls and quality assurance processes (Kechagias et al., 2023). For a traceability system to work effectively, it needs to be present

in each step of the FSC; however, traceability systems are often integrated into the further steps of FSCs, and utilising them in the entirety of FSCs is still an exception (Bhat et al., 2022). Therefore, integrating traceability mechanisms at the production level is considered an important requirement to enhance transparency in FSCs. One of the biggest challenges for traceability is ensuring data integrity and security, as some actors still find ways for data tampering or falsification within existing traceability measures (A. Singh et al., 2023). Another challenge is linked to the complexity and fragmented structure of FSCs due to the coordination of numerous actors with various practices and systems that make it difficult to develop unified traceability standards (K. Li et al., 2023). Similar to Requirement 2, data management is also a challenge here because of the need to collect, store, and analyse large volumes of data. Additionally, building seamless traceability systems could be costly and require sufficient infrastructure (Verdouw et al., 2016).

Regarding data integrity and security, blockchain technology (BCT) offers some solutions by creating immutable and tamper-proof records of production activities and product movements (Cocco et al., 2021). This feature makes it easier to trace back to the records in case of an issue, which improves accountability for the involved parties. However, blockchain technology is mainly a data storage and management solution, and it does not guarantee the accuracy or the quality of data added to the ledgers (Kechagias et al., 2023). For data accuracy and quality, it would be beneficial to integrate IoT sensors or RFID tags to improve the robustness of the traceability system while significantly reducing the complexity and fragmentation in supply chain data management (Cocco et al., 2021; Khanna et al., 2022). The actors should also consider potential security issues linked to using IoT sensors and take measures to enhance the security of their systems with one of the solutions listed under Requirement 2 (encryption, authentication, regular firmware updates, network security, and TinyML). Similarly, data storage (cloud storage, hybrid storage, data lakes, edge computing, and blockchain technology) and data analysis (AI and big data analytics) solutions could be considered depending on resource and skill constraints. As the main characteristic of traceability mechanisms is to allow the user access to actionable data, integrating mobile and web applications with a user-friendly interface would be beneficial (Ferrández-Pastor et al., 2022). Finally, implementing global data standards and developing interoperability protocols would improve the traceability system, although adopting these standards and frameworks requires collaboration among all FSC acors (Keogh et al., 2020).

Requirement 4: Compliance and Certification

The food sector is a highly regulated sector with a focus on food safety, health, and sustainability concerns, which makes it crucial to ensure compliance with the regulations (Trienekens et al., 2012). In addition to the regulations, there are numerous certification schemes in the sector that are

voluntary-basis in essence but have become an important requirement due to their high acceptance and prevalence, regardless of their voluntary nature (Mol & Oosterveer, 2015). Today, we frequently see FSC actors turning to certification schemes to provide quality assurance and improve market access. However, both regulations and certification schemes can get highly complex and trying to navigate and comply with various local, national, and international standards can be complicated and time-consuming because of the documentation burden (Squatrito et al., 2020). This could be especially an issue for small-scale producers due to their intense workload and lack of labour (Parry et al., 2005). It might also be the case that some actors lack knowledge and awareness of which standards to meet to comply with regulations and obtain certificates (Squatrito et al., 2020). Additionally, ensuring the conditions for compliance and certification could be challenging as it requires trustable verification and regular audits, which could be very costly (Powell et al., 2013).

Compliance management software solutions could be beneficial to effectively manage the process by helping the actors track compliance with various regulations and certification standards through checklists, reminders, and documentation storage (Längle et al., 2024). The actors could also benefit from mobile and web applications to get easy access to information on standards and certification requirements and receive real-time updates (Umami et al., 2023). As ensuring compliance with standards could get complicated and time-consuming for primary producers, automating some aspects of their operations could make it easier (Kittipanya-ngam & Tan, 2020). Automating data collection through IoT devices would reduce the manual labour for compliance reporting and ensure compliance through continuous monitoring (Kittipanya-ngam & Tan, 2020). For further automation, actors could integrate blockchain technology (BCT) by adding the records of compliance and certifications to tamper-proof nodes for enhanced accountability (Jahanbin, 2022). It would also be beneficial for transparent auditing as it would provide a clear and unalterable trail of compliance activities. The actors could also integrate AI and big data analytics to predict compliance issues (Rabah, 2018).

Requirement 5: Farmer Education and Training

Many initiatives to enhance transparency in FSCs require an increase in the capacity of FSC actors regarding the awareness, knowledge, and skills to successfully adapt to new ways of working as part of the transparency efforts. The small-scale actors operating in the primary production step often experience a digital gap due to a lack of digital literacy and unequal access to infrastructure and technology, which causes some actors to develop prejudices towards these new approaches that make them resistant to change (Nagpal, 2024). The adoption of new methods and technologies is of high importance since it would be difficult to realise other requirements listed above otherwise. This

challenge could be overcome by training farmers on how to use digital tools for record-keeping and monitoring, as well as educating farmers on best practices regarding more sustainable and transparent farming practices (Choruma et al., 2024). The training could also inform farmers on how to increase their yields and profitability and take better measures against potential health and safety issues (Ahikiriza et al., 2022). In this regard, there is a potential for using e-learning platforms with interactive courses and on-site training programs for hands-on experience (Michaelis et al., 2022). Similarly, user-friendly mobile applications could provide training materials to producers in various local languages (Mandi & Patnaik, 2019). Producers could also participate in webinars and virtual workshops to improve their knowledge of transparency-related practices. In relation, community-based programs would be beneficial to stimulate peer learning over best practices and develop local networks for collaboration opportunities (Burton et al., 2017). As an emerging technology in the sector, mixed reality (MR) and augmented reality (AR) tools could improve the impacts of online learning through immersive learning experiences and real-world scenario simulations that would allow farmers to practice and understand complex tasks (Chai et al., 2022).

Requirement 6: Data Accessibility and Sharing

Data accessibility and sharing refers to the ability to easily access, share, and exchange data among various actors in the supply chain. This is an absolute requirement for each step of the FSC, including the primary production, for transparency but also for collaboration and efficiency (K. Li et al., 2023). Here, it is important to note that it is often easier to access data collected in other steps of FSCs, such as processing or transportation, since they include more automated tasks accompanied by digital tools to collect, store, and share data (Kittipanya-ngam & Tan, 2020). On the other hand, there is an increasing demand for transparency from various stakeholders, such as consumers, governments, and financial institutions, which leads to a growing interest in accessing the production data by other FSC actors (Strube et al., 2021). In this context, data accessibility and sharing have become more significant requirements to achieve transparency in this step. Achieving this requires interoperability between different systems or devices to connect, communicate, and exchange information effectively (Astill et al., 2019). However, interoperability turns into a challenge in this context, as there are some other challenges preventing interoperability, such as the diverse data formats and standards, legacy systems, confidentiality concerns, skill gaps, and resource constraints (Durrant et al., 2021).

To overcome the interoperability challenges to ensure data accessibility and sharing, creating open data platforms that use standardised APIs might be beneficial as they overcome the challenge of diverse data formats and standards and allow seamless data exchange between different systems (Kalatzis et al., 2020). Another option would be middleware solutions, which can also enable

communication between different systems regardless of their underlying hardware and software platforms (Dave & Mittapally, 2024). As a data storage solution, cloud-based platforms with data integration services could be preferable to store data and give secure access to relevant stakeholders, which can be combined with Blockchain technology (BCT) to decentralise data sharing in a reliable manner (Tao et al., 2021). Regarding the confidentiality concerns in data access and sharing, integrating federated learning technology could be an effective solution as it enables data sharing among stakeholders by keeping the data local and only sharing ML model updates (Durrant et al., 2022). This way, the actors would not need to share raw data which also reduces the need for standardised data formats. It also facilitates collaborative learning due to the collaboration of different systems to improve ML models (Durrant et al., 2022).

Requirement 7: Financial and Technical Support

When discussing the digital transition of FSCs for transparency, it is essential for the actors to have access to sufficient financial and technical support. This is especially a crucial requirement for the actors in the primary production step as they are one of the most vulnerable groups to facing obstacles in this regard (Odubote & Ajayi, 2019). These actors experience resource constraints in relation to their limited financial resources and the high initial costs of purchasing and implementing some technologies (Yigezu et al., 2018). Additionally, many rural areas lack local experts who can provide guidance and support, and the continuous advancements in digital tools require ongoing training (Choudhary & Bansal, 2022). There are also adoption challenges resulting from inadequate infrastructure and the difficulty of scaling technology solutions to fit small-scale operations (Kos & Kloppenburg, 2019). Some farmers demonstrate resistance to change due to having lack of trust in the potential benefits of using digital technologies (Smidt & Jokonya, 2022). In addition, they might not be aware of available financial and technical support options.

Providing farmers with the necessary financial resources to adopt new technologies and practices allows them to afford the initial investments, and with ongoing technical support, farmers can maintain and benefit from these technologies in the long term (Maru et al., 2018). One of the digital solutions to the financial challenges would be subsidies and grants management systems that streamline the application process via online portals of governments or NGOs (Tolstolesova et al., 2021). These systems could also integrate blockchain technology to track the financial flow and reduce fraudulent behaviour through smart contracts (Tripoli & Schmidhuber, 2018). Farmers could also benefit from digital financial platforms to raise funds from global investors (Suasih et al., 2022). Regarding the technical challenges, some digital platforms could support farmers with e-learning modules and webinars on best practices and new technologies (Choruma et al., 2024). Additionally,

mobile and web applications could provide remote technical support through virtual consultations or AI-powered chatbots (Chandolikar et al., 2022). Last but not least, collaborative initiatives within public-private partnerships play a key role in making these technology solutions available (Maru et al., 2018).

Requirement	Importance	Challenge	Technology Solution
Detailed record-keeping	Accountability, quality control, compliance, and market access	Manual data entry, lack of digital literacy, resource constraints, and variability in farming practices	Mobile and web applications, data collection tools (IoT devices, drones, and satellites), cloud-based platforms, and BCT
Real-time monitoring and reporting	Crop management, resource efficiency, and sustainability	Limited access to and familiarity with technology, infrastructure limitations, and data management issues (data volume and security)	Cost-effective IoT sensors, drones and satellites, encryption, authentication, regular firmware updates, network security, TinyML, cloud-based storage, hybrid storage solutions, edge computing, data lakes, BCT, mobile applications and dashboards, AI, and ML
Traceability mechanisms	Consumer trust, quality assurance, food safety, recall management, fraud prevention, and market access	Data integrity and security, complexity and fragmentation, data management, cost and infrastructure limitations	BCT, IoT sensors or RFID tags, encryption, authentication, regular firmware updates, network security, TinyML, cloud-based platforms, hybrid storage solutions, edge computing, data lakes, mobile and web applications, AI and big data analytics, global data standards and interoperability frameworks
Compliance and certification	Market access, regulatory requirements, and quality assurance	Complexity and the amount of regulatory requirements and standards, documentation burden on small-scale actors, and the cost of compliance	Compliance management software, mobile and web applications, e-learning platforms and on-site training, automation, IoT devices, BCT, AI and big data analytics
Farmer education and training	Capacity building, creating awareness, improving skills, technology adoption, and best practices	Digital gap, prejudice, resistance to change, access to training resources	E-learning platforms, mobile applications, on-site training programs, webinars and virtual workshops, community-based programs, and MR and AR

Data accessibility and sharing	Collaboration, visibility, and efficiency	Interoperability issues (diverse data formats and standards, legacy systems, confidentiality concerns, skill gaps, and resource constraints)	Open data platforms, standardised APIs, middleware solutions, cloud-based platforms, BCT, and federated learning
Financial and technical support	Affordability and long-term support	Resource constraints, lack of local experts, ongoing training needs, inadequate infrastructure, scalability, resistance to change, and lack of awareness	Subsidies and grant management systems (online portals and smart contracts), digital platforms (fundraising, e-learning, and webinars), mobile and web applications (virtual consultations and AI-powered chatbots), and public-private partnerships

Table 1. Connections within the primary production step

2.1.2 Processing

Processors were one of the consistently identified stakeholders in D2.1 and the report states that what the processing step may entail can be very different depending on the supply chain. In relation, it could be a big actor like Heineken, a small company assisting with the processing, or a food company doing the processing itself. D2.1 also highlights the fact that processing can occur in different stages of the same supply chain and it is a complex step. In general, the processing step can be defined as transforming agricultural materials into consumable food products or ingredients to be used in other food products. Processing activities can range from simple tasks such as washing and cutting to more complex tasks like pasteurisation, fermentation, cooking, freezing, or chemical processing (Ghosh, 2014). It is a crucial step for contemporary diets as the raw materials are modified to enhance shelf life, safety, taste, or convenience for consumption (Ghosh, 2014). This step involves a considerable level of digitalisation, and it is subject to intensive control in accordance with food safety regulations and standards (Lam et al., 2020). In this context, ensuring food safety appears to be the focal point of the transparency initiatives in this step, along with consumer trust, regulatory compliance, and brand reputation (Akkerman et al., 2010). According to the findings in the D2.1 report, processors' interest in transparency may be motivated by retailers' requests, and the processors are increasing their control over other FSC steps as well. Consequently, this dynamic can result in the emergence of new requirements and challenges in the context.

Connections Between Requirements, Challenges, and Technology Solutions

Requirement 1: Compliance with Food Safety and Quality Standards

The actors operating in this step have to comply with food safety and quality standards, whether they are global standards such as HACCP and ISO 22000 or local standards. The consequences of non-compliance could lead to health risks, legal enforcement, and irreparable damage to the brand's reputation (Trienekens & Zuurbier, 2008). Naturally, compliance with food safety and quality standards appears to be an important requirement for creating transparency in this step, and it is strongly connected to the realisation of other requirements in this context. However, there are several challenges the food processors experience to meet this requirement, such as the complexity of regulatory requirements as the regulations vary across regions and products, which can get overwhelming to keep up with all (Kotsanopoulos & Arvanitoyannis, 2017). As safety regulations evolve continuously, the actors need to adapt rapidly to new changes, which can also get overwhelming (Madilo et al., 2024). Food processors also need to verify their suppliers and ingredients in accordance with food safety standards, which can be challenging in complex, global FSCs (Górska-Warsewicz et al., 2021). Additionally, the risk of non-compliance increases because of human error and inconsistent implementation of safety protocols (Madilo et al., 2024).

There are several digital technologies that would help the actors overcome such challenges. One of the solutions would be using regulatory compliance software to track and manage compliance and stay updated with the latest regulations (Padmanaban, 2024). These tools can be powered by AI and ML to analyse the current processes and provide recommendations on necessary adjustments, which can also include alerts when the regulations change, and the actions are no longer compliant (Padmanaban, 2024). E-learning platforms could also support compliance with new regulations through continuous learning, which can be integrated into compliance management systems (Chavan et al., 2024). Furthermore, the actors could create digital twins to simulate the entire process and test changes associated with new regulations before compliance to reduce the complexity (Maheshwari et al., 2023). To reduce human error, the actors could automize related tasks such as automated inspection systems along with the integration of IoT devices (Abass et al., 2024). With cloud-based quality management software (QMS), the actors could store this data on the cloud and have access to real-time data to identify and correct deviations swiftly (Barlow et al., 2020). Food processors can also have recourse to blockchain technology (BCT) to create immutable records of compliance activities and enhance accountability. By integrating smart contracts as a BCT function, the actors can also automate compliance verification processes (Luna et al., 2024). This would also improve supplier verification by tracking the compliance statuses of all suppliers. AI tools can also be used to support

supplier management either via analysing the data received by the suppliers or publicly available data published by national food safety authorities (Stoitsis et al., 2023).

Requirement 2: Real-Time Monitoring and Reporting

Collecting real-time data is crucial for food processors to detect and give timely responses to the issues that occur in processing (Armbruster & MacDonell, 2014). This capability reduces the risk of unsafe products reaching the market and any potential breaches of food safety and quality standards (Armbruster & MacDonell, 2014). Additionally, real-time monitoring is essential to apply and maintain the necessary sustainability measures (Kittipanya-ngam & Tan, 2020). Food processing happens in fast-paced environments, including various and complex steps that require control over several parameters, such as temperature, humidity, and sanitation (Hassoun et al., 2023). Such data would only be meaningful when collected in real-time. However, it is not an easy goal to achieve integrated monitoring systems as many processors use a variety of data collection tools that result in data silos (Dooley et al., 2018). Additionally, real-time data collection tools generate vast amounts of data, which results in data management and storage issues (Lee & Lee, 2015). Food processors also need to ensure the accuracy and reliability of the real-time data in case of malfunctions in the sensors, data corruption, and communication failures (D. Li et al., 2020). Furthermore, real-time data can reach its full potential if the data can be processed quickly to support real-time decision-making. Since many real-time monitoring systems are connected to the internet, they become vulnerable to cybersecurity risks (Streng, 2019). These systems also need to be scalable if the data volume and complexity of the processing operations increase. Real-time monitoring systems can involve high implementation and maintenance costs, which can impede scaling efforts (Narwane et al., 2022).

Industrial IoT (IIoT) platforms could be beneficial to tackle the data silos issue as they can integrate data from various sensors and systems across the facility and enable centralised data (Mantravadi, 2023). Middleware solutions are another solution to bridge disparate systems as well as integrate new technologies into older legacy systems (Branco et al., 2021). To analyse large amounts of real-time data, processors need solutions to deal with the quantity of such data in real time. AI and ML tools and big data analytics can analyse large amounts of data in real-time, identify patterns, and provide alerts to support real-time decision-making (Ding et al., 2023). To reduce the need for data storage, the actors could consider using edge computing, which can modify, filter, and compress data through edge analytics (Nayak et al., 2024). Regarding data accuracy and integrity concerns, self-diagnosing and self-calibrating sensors could be used for data collection (Micheler et al., 2019). Integrating TinyML into the system would also increase the possibility of collecting accurate and reliable data (Tsoukas et al., 2022). The costs linked to real-time monitoring systems can be reduced by pay-as-you-

go pricing models, which enables the actors to start small and scale up when necessary (Haga & Omote, 2021). Cloud-based solutions are also effective in reducing costs, and they allow scalability as they allow users to increase their data processing capacity without additional hardware (Bahga & Madisetti, 2013). Another solution to scalability issues would be modular monitoring systems with the ability to add new sensors without overhauling the entire system (Alonso et al., 2020). Depending on the technical expertise level of the users, there are cost-effective open-source solutions that reduce the licensing cost and offer greater customisation (Ayele et al., 2024). Concerning the cybersecurity risks, the actors can implement strong encryption protocols for data transmission and use AI-powered cybersecurity tools to continuously monitor unusual activities (G. Ali et al., 2024).

Requirement 3: Automated Quality Control and Reporting Mechanisms

Automating the quality control and reporting processes allows food processors to ensure that all products consistently and efficiently meet the food quality and safety standards (Liberty et al., 2024). Automation reduces the risk of human error and enhances transparency through continuous oversight, and is dependent on real-time monitoring and reporting (Liberty et al., 2024). Therefore, some of the challenges that could arise in this requirement are similar to the challenges linked to real-time monitoring, such as high initial costs and investment, ensuring data accuracy and consistency, and scalability and flexibility. The other challenges that could be relevant are integration with the existing systems, resistance to change and workforce adaptation, and continuous improvement and adaptation (Terra et al., 2021). In an automated system, the data collection is done via automated data capture systems such as barcodes, QR codes or RFID tags. To create an integrated and automated quality control system, the actors could benefit from IoT platforms that connect various devices and systems (Popa et al., 2019). The real-time analytics dashboards can display this monitoring data for easier reporting and informed decision-making (Konur et al., 2023). In combination, AI-driven decision-making systems (DMS) can improve the analysis of real-time data and provide recommendations (Konur et al., 2023). Another solution would be using edge computing to analyse real-time data at the edge to give immediate responses without relying on central information systems (X. Zhang et al., 2020).

The integration of new automated systems into the existing legacy systems could be realised via integration middleware or API-based integration (Dave & Mittapally, 2024). Similar to real-time monitoring, the accuracy and integrity of data can be improved by using self-diagnosing and self-calibrating sensors or AI and ML tools to detect abnormalities and inconsistencies in real-time (Devineni, Kathiriya, et al., 2023; Micheler et al., 2019). Building automated systems also needs cybersecurity measures such as encryption and network security. As mentioned in the previous

section, cloud-based quality management platforms (QMS) could enable scalability, along with modular automation systems, which can be configured and expanded to improve flexibility (Barlow et al., 2020). Such automated systems need to evolve and improve over time to stay effectively relevant (Tancredi, 2024). In this context, AI-powered adaptive systems can dynamically adjust quality parameters, and automated feedback loops support this continuous adjustment process based on real-time data (Tancredi, 2024). Another solution would be using digital twins to test and optimise quality control processes virtually (Tancredi, 2024). Another similarity to real-time monitoring solutions is that setting up automated quality control systems requires significant investment in equipment, software, and training (Rüßmann et al., 2015). To reduce costs, the actors could prioritise solutions with pay-as-you-go or subscription payment models (Haga & Omote, 2021). Cloud-based quality control platforms also reduce the initial cost and offer flexibility and scalability (Bahga & Madisetti, 2013). When food processors decide to adopt new automated quality control systems, the workforce might resist such a change due to the fear of job loss, lack of understanding of the new tools, or discomfort with their new way of working (Liberty et al., 2024). Food processors can respond to these concerns by investing in collaborative robots to take on repetitive and dangerous tasks while leaving the decision-making tasks to their employees (Liberty et al., 2024). As this arrangement would still require upskilling of the employees, comprehensive training programs need to take place to enhance awareness of the new system, along with technical training to teach how to use these new tools (Liberty et al., 2024). It is also important to ensure that the new system interface is intuitive and user-friendly.

Requirement 4: Standardized Documentation and Record-Keeping

Standardized documentation and record-keeping refers to the uniformity in documentation content across FSCs for consistent data collection, analysis, and sharing, and it is closely linked to interoperability standards, which refers to the operational processes that enable diverse systems to communicate and share standardized data (Olsen, 2018; Sansone & Rocca-Serra, 2016). This requirement is crucial for ensuring transparency, traceability, auditability, and compliance with regulations and standards (Okpala & Korzeniowska, 2023). However, achieving standardised documentation is a difficult task to achieve, and there are several challenges to overcome. Some of these challenges are inconsistent data entry (Zeb et al., 2021), the proliferation of standards (Trienekens & Zuurbier, 2008), complexities due to variations in regulations (Eruaga, 2024), data privacy concerns (Jabbar et al., 2021), and continuous updates and version control (Flügge et al., 2011). Considering the complexity and fast-paced characteristics of the processing step, the chances of achieving standardised documentation are higher when the data is collected via automated data capture systems. In some settings, the actors could use natural language processing (NLP) tools to

automate the documentation process by transcribing written or verbal inputs into standardised formats (Schöpper & Kersten, 2021). Different facilities in FSCs may use different documentation formats, and such inconsistency causes difficulties in the analysis and comparability of data across the entire operation (Akyar, 2012). For this, standard operating procedures (SOP) software can be used to create and enforce standardized procedures for documentation (Akyar, 2012). The actors in different facilities can also use blockchain technology to record every entry in a standardised format and enforce unified documentation (Cao, Xu, et al., 2023). Another solution would be a cloud-based centralised documentation platform as a single system for unified record-keeping (Rasheed et al., 2024).

In fast-paced environments such as food processing, having real-time access to documentation is highly important for decision-making, audits, and traceability. Digital document management systems (DMS) allow food processors to centralise and organise their documents for efficient search and retrieval (Jordan et al., 2022). Depending on the complexity of the operations, the actors could also benefit from AI-powered search tools to go through large volumes of documentation and retrieve relevant information instantly (Mahadevkar et al., 2024). In addition, having mobile-friendly documentation systems allows authorised users to access documents easily and remotely (Sallabi et al., 2011). These solutions are closely connected to ensuring data security and integrity since many of these documents contain sensitive information. One measure would be protecting the documents with end-to-end encryption during data transmission and storage (Tanwar et al., 2022). Blockchain technology (BCT) is a promising solution in this regard, as the documents can be stored in immutable ledgers, each being encrypted and time-stamped to ensure their integrity (Tanwar et al., 2022). The actors would also need role-based access control mechanisms (RBAC) to minimise the risk of unauthorised access (Kaushal et al., 2024). To deal with the complexity of regulatory compliance, the actors could implement regulatory compliance management software and AI-driven compliance audits to ensure the documentation is executed as it is supposed to be (Längle et al., 2024; Padmanaban, 2024). In addition, the actors could use cloud-based collaborative platforms to make the updates in real time and give relevant stakeholders access to the latest version (Kopanaki et al., 2018).

Requirement 5: Traceability Mechanisms

End-to-end traceability is considered one of the main requirements for creating transparency in FSCs, and processing is a key step in the journey of food products as this is where the raw materials can undergo several transformations, which makes it essential to maintain traceability to reduce the risk of contamination or fraud and address issues quickly and effectively in the event of a recall

(Demestichas et al., 2020). This capability is also the key to ensuring compliance with regulations and standards and maintaining the brand's reputation for quality (Stranieri et al., 2021). Even though there are nuances regarding the context of traceability in different steps of FSCs, the challenges in this regard are more or less the same, namely, the complexity and fragmented structure of FSCs (Akkerman et al., 2010), data interoperability issues (Ringsberg, 2014), ensuring data accuracy and integrity (Caro et al., 2018), scalability issues (Islam, Cullen, et al., 2021), and data privacy and security concerns (Malik et al., 2021). In order to prevent repetition, the possible technology solutions that were previously explained are mentioned more briefly in this section.

To deal with the complexity of the processing step, the actors could use supply chain management software (SCMS), which can integrate data from various sources and include tracking features (Haulder et al., 2019; Kumar et al., 2020). The use of IoT devices is a considerable solution here as well for collecting real-time data and tracking the movement of food products (Opasvitayarux et al., 2022). The accuracy and integrity of this data also need to be taken care of, and AI and ML algorithms could be used to validate data, while blockchain technology (BCT) could be beneficial for data integrity (Tsolakis et al., 2023). For interoperability issues, the actors can facilitate API-based integration (Kalatzis et al., 2020), middleware solutions (Dave & Mittapally, 2024), and data standardisation protocols (Keogh et al., 2020). The collection and sharing of large amounts of data raises confidentiality concerns in traceability, and ensuring data privacy and security is a challenge (Malik et al., 2021). As previously mentioned, blockchain technology (BCT) can be a viable solution with end-to-end encryption (Tanwar et al., 2022), as well as implementing role-based access control (RBAC) measures (Kaushal et al., 2024). Additionally, the actors could consider applying zero-knowledge proofs (ZKP), which is a cryptographic technique that allows data verification without exposing sensitive data (Sahai et al., 2020). Finally, food processors can integrate cloud-based traceability solutions to scale up their traceability capabilities in parallel to their growing operations (Islam, Manning, et al., 2021).

Requirement	Importance	Challenge	Technology Solution
Compliance with food safety and quality standards	Public health, legal obligations, and brand reputation	Complexity, variation, and continuous evolution of regulatory requirements, supplier verification, and human error	Regulatory compliance software, AI and ML tools, e-learning platforms, digital twins, automatization, IoT devices, cloud-based QMS, BCT, and smart contracts

Real-time monitoring and reporting	Food safety and quality, sustainability, timely response, informed decision-making	Data silos, data management and storage, data accuracy and reliability, data processing, cybersecurity, implementation and maintenance costs, and scalability	IIoT platforms, middleware solutions, AI and ML tools, big data analytics, edge computing, self-diagnosing and self-calibrating sensors, TinyML, pay-as-you-go pricing models, cloud-based monitoring solutions, modular monitoring systems, open-source solutions, encryption protocols, and AI-powered cybersecurity tools
Automated quality control and reporting mechanisms	Reducing human error, real-time monitoring, continuous oversight, and efficiency	High initial costs and investment, data accuracy and consistency, cybersecurity, scalability, flexibility, integration with the existing systems, resistance to change and workforce adaptation, and continuous improvement and adaptation	Automated data capture systems, IoT platforms, real-time analytics dashboard, AI-driven DMS, edge computing, integration middleware, API-based integration, self-diagnosing and self-calibrating sensors, AI and ML tools, encryption, network security, cloud-based QMS, modular automation systems, AI-powered adaptive systems, automated feedback loops, digital twins, pay-as-you-go/subscription payment models, collaborative robots, comprehensive training programs, and intuitive and user-friendly interface
Standardized documentation and record-keeping	Interoperability, traceability, auditability, and compliance	Inconsistent data entry, the proliferation of standards, complexity in regulatory compliance, data privacy concerns, and continuous updates and version control	Automated data capture systems, NLP, SOP software, BCT, cloud-based centralised documentation platform, digital DMS, AI-powered research tools, mobile-friendly solutions, end-to-end encryption, RBAC, regulatory compliance management software, AI-driven compliance audits, and cloud-based collaborative platforms
Traceability mechanisms	Public health, preventing food fraud, quick and effective response to recalls, compliance with regulations and standards, and brand reputation	Complexity and fragmented structure of FSCs, data interoperability issues, ensuring data accuracy and integrity, scalability issues, and data privacy and security concerns	SCMS, IoT devices, AI and ML algorithms, BCT, API-based integration, middleware solutions, data standardisation protocols, end-to-end encryption, RBAC measures, ZKP, and cloud-based traceability

Table 2. Connections within the processing step

2.1.3 Transportation

Transportation refers to the physical movement of food products between various FSC steps through road, rail, maritime, or air transport, and it is mainly concerned with the vehicles, routes, and processes to move the items effectively (Cedillo-Campos et al., 2023). Various types of food products (from raw materials to finished products) are moved between locations, and this brings a significant complexity to ensuring the optimal conditions specific to each food product type (Gharehgozli et al., 2017). Key activities in this step depend on the supply chain, but in general terms, these activities might incorporate route planning, cold chain management, loading and unloading, and packaging (Awad et al., 2021). The key actors fulfilling these tasks could be transport providers and third-party logistics providers (3PLs) (Granillo-Macías et al., 2023). Customs and regulatory agencies are also significant stakeholders influencing the activities in this step (Martincus et al., 2013). Regarding the transparency creation in the transportation step, the D2.1 report discusses the lack of ownership transporters feel regarding the products they move, leading to disinterest in the product information. Correspondingly, the report concludes that there may be other FSC actors who might be more engaged in FSC transparency as a starting point. Even so, transparency creation in the transportation step needs to be considered due to the vulnerability of food products to various risks (such as contamination and spoilage), which can have serious consequences for food safety and public health, especially in the case of long and global supply chains (Granillo-Macías et al., 2023). These issues could also lead to legal consequences as well as damage to brand reputation and consumer trust (Bosona & Gebresenbet, 2013). Transparency initiatives in this step can support the actors in better risk management and improve the efficiency and sustainability of their operations, including the reduction of carbon footprint (Granillo-Macías et al., 2023; Vernier et al., 2021).

Connections Between Requirements, Challenges, and Technology Solutions

Requirement 1: Real-Time Tracking and Monitoring

In the context of transportation, real-time data collection is required to create transparency on the exact location and conditions of food products at any given time (Jagtap et al., 2021). This enables the actors in this step to ensure the products arrive at their destination on time and in good condition, which is crucial for preventing food fraud, reducing spoilage, contamination, and food waste, ensuring compliance with food safety standards, and managing inventory (Jagtap et al., 2021). Real-time tracking is also important for route optimisation and reducing the CO_2 emissions of the operations (Helo & Ala-Harja, 2018). As previously mentioned, achieving real-time monitoring requires technology integration, and some small actors may struggle with the complexity and initial costs of integrating such technologies (Bosona & Gebresenbet, 2013). When actors integrate real-time data

collection technologies, they end up generating large volumes of data and need to find proper data storage and analysis solutions, which can be overwhelming (da Costa et al., 2024). They would also need to ensure the accuracy and reliability of this data, and issues like signal loss in remote areas or equipment malfunctions can lead to data gaps and reliability issues (Jagtap et al., 2021). Additionally, real-time tracking and monitoring involve handling sensitive data, which might attract cyberattacks and ensuring the privacy and security of this data can be challenging for some actors (Cheung et al., 2021).

To make technology integration more convenient for the actors in this step, cloud-based logistics platforms could be a viable option as they can easily integrate with the existing systems and scale up when necessary, which can reduce the complexity and initial cost of integration (Islam, Manning, et al., 2021). These platforms provide a centralised monitoring system, and various tracking technologies such as GPS, IoT sensors, and RFID tags can connect to such central platforms and simplify integration (M. K. Sharma et al., 2022). The integration of API is another possible solution due to seamless data exchange between different systems (Dave & Mittapally, 2024). To deal with data overload, the actors can use edge computing to analyse data locally, which reduces the load on the central system for storage and enables faster data processing (Nayak et al., 2024). With data aggregation tools, the actors can aggregate data from multiple sources and simplify data analysis (Rejeb et al., 2022). In addition, automated reporting systems can be used to reduce the need for manual data analysis, and the actors can also integrate AI and ML algorithms into their systems to filter and analyse the data and generate automated reports (Jagtap et al., 2021). Data visualisation software is another possible solution to present large and complex data in a simplified format (Gunawan et al., 2019). To improve the accuracy and reliability of real-time data, the actors can cross-verify sensor data or use AI-powered analytics to detect abnormalities (Devineni, Kathiriya, et al., 2023). The actors can also apply predictive maintenance with AI to predict and address equipment failures before data use (Jagtap et al., 2021). To deal with privacy and security concerns, The actors can use IoT platforms with built-in security features or implement end-to-end encryption (Ukil et al., 2011). For an additional layer of security, the actors can implement authentication protocols for access control (Anandhi et al., 2019).

Requirement 2: Documentation and Record-Keeping

Proper documentation and record-keeping have a central position in transparency initiatives in transportation through recording every action, condition, and movement of food products (A. M. Sharma et al., 2024). The tracking and monitoring data is needed for documentation to ensure food safety and quality. Through documentation, the actors would be able to improve quality control processes, audits, traceability, and compliance (Bosona & Gebresenbet, 2013). In the previous

requirement, we highlighted the importance of real-time data; however, manual data entry is still commonly used in transportation, which causes human error problems (Islam, Manning, et al., 2021). This is possibly due to the varying technological capabilities of several FSC actors involved in the transportation process. The lack of standardised documentation procedures across these actors is another challenge hindering the successful implementation of this requirement (A. M. Sharma et al., 2024). Additionally, the actors might face resistance regarding new documentation practices from employees and business partners who are used to less rigorous processes (I. Ali & Aboelmaged, 2021).

Automated data collection tools (RFID tags, sensors, barcodes, voice recognition, etc.) are one of the most effective ways to reduce the reliance on manual data entry. The actors can also use AI-powered document processing to validate and correct human errors in documents (Tsolakis et al., 2023). For standardised documentation, the actors can agree to adopt global data standards relevant to their supply chain (Keogh et al., 2020). Electronic data interchange (EDI) systems are another solution that enables standardised data exchange between different systems while minimising human intervention (Füzesi et al., 2016). The actors can also use the templates provided by cloud-based collaboration platforms to improve collaboration on standardising the documentation process (Kassahun et al., 2014). Depending on the context, blockchain technology (BCT) can be useful to enforce standardisation as it requires all parties to use the same format to store documents on shared ledgers (Cao, Xu, et al., 2023). Regarding the resistance to change, it is important to have user-friendly interfaces in the newly adopted documentation tools. The actors could also set up incentivisation platforms to track compliance with new documentation practices and motivate the employees with rewards or recognition (P. K. Singh & Maheswaran, 2024).

Requirement 3: Traceability Mechanisms

Traceability allows for having historical track records on the action, condition, and movement of food products and this way, the actors would be capable of tracing back through each step of the FSC in the event of a food safety incident and take corrective actions. Since the transportation step connects various FSC steps to one another, it brings the risk of spreading the scale of food safety risks to other FSC steps, especially when it comes to cross-contamination (Ackerley et al., 2010). Therefore, the transportation step has a key position to ensure end-to-end traceability throughout the FSC. Similar to other steps, ensuring traceability in this step is also crucial for recall management and brand reputation (Chhikara et al., 2018). Most FSCs already have some traceability mechanisms in place as a result of regulatory requirements. However, achieving complete traceability is highly challenging for most FSCs due to their complexity and global character (Akkerman et al., 2010), which is closely linked to transportation operations. Improving existing traceability mechanisms with the implementation of

new tools could be costly, and some actors may lack the incentive to implement such new measures if they do not see the direct benefits (Nishantha et al., 2010). Another challenge would be heterogeneous data that hinders seamless data sharing among all parties due to incompatible systems or a lack of standardised protocols (Bicocchi et al., 2019; Bosona & Gebresenbet, 2013).

One way to reduce the complexity of traceability initiatives would be the use of digital twins to simulate different scenarios to manage complexities through knowledge mapping (Maheshwari et al., 2023). By analysing vast amounts of data, AI-powered supply chain management tools could identify patterns and predict issues to reduce complexity as well (Goswami et al., 2022). The use of blockchain technology (BCT) could also be useful for managing complex traceability processes by keeping the records of the product's journey on decentralised ledgers (Iftekhar et al., 2020). Concerning the costs of traceability mechanisms, cloud-based traceability platforms could be adopted due to their scalable and pay-per-use models to reduce the initial investment required for implementation (Cerullo et al., 2016). Transportation companies can also join consortium blockchain networks to share the costs of developing and maintaining new traceability mechanisms (X. Li et al., 2020). Additionally, some blockchain solutions provide high modularity (e.g. Hyperledger Sawtooth) for better customisation and scaling (Baralla et al., 2019). In case of a lack of incentive, influential actors can integrate smart contracts, which enforce traceability measures by default and provide incentives to other actors based on compliance and data sharing (Kumarathunga, 2020). There are also market-driven incentives, such as industry certification programs, that require traceability to enter specific markets (Charlebois et al., 2014). To deal with heterogeneous data, cloud-based solutions are considered beneficial for better integration (Goldstein et al., 2022). In this context, the Cloud of Things (CoT) has emerged as a framework and technology solution to integrate distributed data sources and manage the data flow through cloud services for better flexibility (Yan et al., 2014).

Requirement 4: Compliance with Regulatory Standards

The movement of food products on the local, national, and international scales depends on regulatory compliance in the transportation step, and non-compliance can result in legal repercussions, penalties, product recalls, and damage to brand reputation (Marucheck et al., 2011). As the majority of regulations focus on food safety and quality, the main purpose of creating transparency in relation to regulatory compliance would be protecting public health (Lam et al., 2020) and gaining/maintaining access to markets (Soon et al., 2020). Regulatory standards include adherence to various subjects, such as temperature level control, packaging, labelling, and documentation (Bosona & Gebresenbet, 2013). These standards need to be met in other FSC steps, and they need to be maintained during the transportation step. However, the actors in this step face challenges similar to other steps regarding

ensuring regulatory compliance. Having to navigate across varying regulatory environments is challenging for this step, as this is when the products move across regions (Grover, 2023). Staying up-to-date with continuously changing regulations is also a challenge here, and even more so when the actors lack the expertise or resources to follow and comply with all the standards (Mitchell, 2003). Additionally, some areas have weaker regulatory enforcement, leading to a culture of non-compliance (Hirschauer et al., 2012). As the transportation of global FSCs incorporates several stakeholders from various locations, such non-compliance can damage the transparency of the entire operation and lead to serious consequences.

The issue of varying regulations was mentioned in previous sections, and it can be addressed with regulatory compliance management platforms (Längle et al., 2024) or AI-driven compliance monitoring (Palakurti, 2022). These tools can also inform the users of the changing and conflicting requirements for necessary adjustments. The use of cloud-based services in combination with these solutions would reduce the cost of compliance (Kassahun et al., 2014). The actors can also automate their compliance audits for regular checks against regulatory changes (Castka & Searcy, 2023). If the actors would like to develop insight into future possible regulations, they can implement machine learning (ML) algorithms to analyse trends and historical data (Misra et al., 2022). The development of AI-driven virtual compliance assistants could also provide regulatory support when the actors are not able to have an internal legal team or outsource experts (Djadi & Toubal, 2024). This would be a suitable fix for simple issues; however, it would not be able to replace the expertise of a legal professional on more detailed and complex cases. Another solution could be crowdsourced compliance platforms, where the actors can share compliance resources and information and reduce the burden and cost of staying compliant (Qutab et al., 2023). In case of enforcement gaps due to the non-compliance of some business partners, the actors in this step can benefit from using blockchain technology (BCT) to verify compliance through immutable records of compliance activities (Luna et al., 2024). Furthermore, they can implement smart contracts to automatically enforce compliance with pre-set conditions and generate alerts or penalties when conditions are not met (Luna et al., 2024).

Requirement 5: Effective Communication and Collaboration

Effective communication among all the parties involved in the transportation step is important for achieving transparency in FSCs, and it involves the communication of delays, changes in the condition of the food products, potential risk for contamination, and updates on the inventory levels (Jagtap et al., 2021). Without open and transparent communication, the problems can go unnoticed, and the actors cannot effectively collaborate, making the supply chain vulnerable to delivery failures, food

safety incidents, spoilages, food waste, and legal liabilities. Here, the key concern is to promptly address the issues, share critical information, and coordinate (van Beusekom – Thoolen et al., 2024). When communication is open, there would be less chance for misunderstandings and confusion as everyone would be well-informed and aware of their responsibilities. However, achieving this is not an easy task, and there are some challenges to overcome. Open communication requires trust among stakeholders, which is difficult to create in competitive environments due to confidentiality concerns (Krumpholz et al., 2021). These stakeholders might have different priorities and commitment levels to transparency and it might create conflicting situations. Additionally, language and cultural differences in global FSCs can lead to misunderstandings and miscommunications, which hinder effective communication and collaboration (Reynolds, 2024). Finally, the stakeholders might be using disparate systems for data sharing and communication, and this can result in a lack of interoperability and creation of data silos (Ameh et al., 2024).

To improve trust among stakeholders, there should be solutions addressing data access control and data privacy aspects. For this, blockchain technology (BCT) can foster trust by storing the data on an immutable ledger to which every participant can have secure access (Tanwar et al., 2022). The actors can develop collaborative platforms with role-based access or encrypted communication tools to ensure confidential and protected data sharing from unauthorised users (Devineni, Karangara, et al., 2023). Collaborative platforms could also be beneficial to align different stakeholder perspectives regarding their transparency priorities and efforts (Gurzawska, 2020). The actors can also create KPIs related to transparency goals and use real-time dashboards to track and display these KPIs (Piela, 2017). To overcome language barriers, the actors can benefit from multilingual communication platforms and AI-powered translation tools (Ozturk, 2024). Regarding cultural differences, the actors can provide cultural sensitivity training supported by digital tools such as gamification or VR and AR for more interactive learning (Masood et al., 2024). To tackle interoperability and data silos, the actors can use API-driven integration, cloud-based collaboration tools, and interoperable data standards, as explained in previous sections regarding the challenge.

Requirement	Importance	Challenge	Technology Solution
Real-time tracking and monitoring	Condition of food products, food fraud, spoilage, contamination, food waste, compliance with food safety standards, managing	Complexity and cost of technology integration, data overload, data accuracy and reliability, and data privacy and security	Cloud-based logistics platforms, GPS, IoT sensors, RFID tags, API integration, edge computing, data aggregation tools, automated reporting systems, AI and ML algorithms, data visualisation software, AI-powered analytics, predictive maintenance with AI, IoT

	inventory, route optimisation, and reducing carbon footprint		platforms with built-in security, end-to-end encryption, and authentication protocols for access control
Documentation and record-keeping	Food safety, quality control, audits, traceability, and regulatory compliance	Manual data entry and human error, standardisation issues, and resistance to change	Automated data collection tools, AI-powered document processing, global data standards, EDI systems, cloud-based collaboration platforms, BCT, user-friendly documentation tools, and incentivisation programs
Traceability mechanisms	Food safety and quality, preventing cross-contamination, recall management, brand reputation, and regulatory compliance	The complexity of global FSCs, the cost of implementation, the lack of incentives, and heterogeneous data	Digital twins, AI-powered SCM tools, BCT, cloud-based traceability platforms, consortium blockchain networks, modular traceability systems, smart contracts, industry certification programs, and cloud-based integration platforms (e.g., CoT)
Compliance with regulatory standards	Food safety and quality, public health, avoiding legal repercussions, penalties, and product recalls, brand reputation, and market access	Variety of regulations in different regions, continuously changing regulations, resource constraints, culture of non-compliance, and enforcement gaps	Compliance management platforms, AI-driven compliance monitoring, automated compliance audits, cloud-based services, ML algorithms, AI-driven virtual compliance assistants, crowdsourced compliance platforms, BCT, and smart contracts
Effective communication and collaboration	Managing delays, changes in environmental conditions, risk of contamination, updates on inventory, food waste, spoilage, legal liabilities, promptly addressing issues, and coordination	Lack of trust, confidentiality concerns and competition, conflicting priorities and commitment to transparency, language and cultural differences, interoperability issues, and data silos	BCT, collaborative platforms (role-based access and encryption), transparency KPIs and performance dashboards, multilingual communication platforms, AI-powered translation tools, cultural sensitivity training supported by digital tools (gamification, AR/VR), API-driven integration, cloud-based collaboration tools, and interoperable data standards

Table 3. Connections within the transportation step

2.1.4 Distribution

The distribution step is a critical point in FSCs, and it is often linked to the movement of finished food products to the market (retailers and consumer channels), as described in the D2.1 report. The

distribution systems can take many forms with a spectrum from distributors operating with one vehicle to publicly traded companies managing a large fleet of vehicles and distribution centres (Rogoff, 2014). There are also other actors expanding their operations towards distribution, such as retailers and processors, as examples from the D2.1 report. In this regard, distribution can be realised by retailers and processors that own distribution centres and networks or transportation companies that also provide warehousing and inventory services. From a general point of view, some of the common activities in the distribution step are warehousing, inventory management, order fulfilment, transportation coordination, demand forecasting, quality control and safety checks, and return management (Manzini & Accorsi, 2013). Transparency initiatives in this step can be focused on food safety, operational reliability, compliance with regulations and standards, consumer trust, efficiency in relation to food waste and cost reduction, inventory visibility, and social responsibility (Rogoff, 2014).

Connections Between Requirements, Challenges, and Technology Solutions

Requirement 1: Real-Time Inventory Tracking and Environmental Condition Monitoring

Food products are moved between locations as part of distribution activities, and the real-time tracking of the inventory provides visibility on the location of the items at any given moment and reduces order errors, delays, and food waste (Jagtap et al., 2021). This is critical for the efficiency of the operations regarding market matching and inventory management of food products during distribution. This step also requires real-time monitoring of the temperature and other conditions during the storage and transportation of food products to ensure food safety and quality (Gallo et al., 2021). The failure to maintain necessary conditions can lead to public health risks, non-compliance with regulations and standards, and damage to brand reputation (Abass et al., 2024). Regarding continuous real-time data generation, one of the biggest challenges would be fragmented systems and data silos due to the involvement of various actors in distribution networks leading to a flow of heterogeneous data (Serazetdinova et al., 2019). Moreover, some of the actors might have issues with covering the cost of real-time data generation tools or have limited technological infrastructure (Narwane et al., 2022). There might also be technical issues, such as sensor malfunctions, battery failures, or connectivity issues resulting in data gaps (Jagtap et al., 2021).

To deal with the issue of fragmented systems and data silos, cloud-based ERP systems (Zadeh et al., 2018), API integration, and middleware solutions in combination with AL and ML could be some options (Dave & Mittapally, 2024). To reduce the costs of implementing real-time data collection technologies, the actors can integrate low-cost sensor technologies (Maksimović et al., 2015), rent IoT equipment (Krishnan et al., 2020), use open-source platforms (Ayele et al., 2024), or choose IoT

equipment providers with pay-as-you-go pricing models (Haga & Omote, 2021). In the case of limited technological infrastructure, the actors can utilise cloud-based systems for tracking and monitoring, which can offer modular IoT solutions (Sergi et al., 2021) and easy access to data via mobile devices (Debauche et al., 2022). Lastly, the technical issues encountered in IoT devices can be tackled by predictive analytics and maintenance tools to address equipment failures (Jagtap et al., 2021). When cloud-based IoT solutions are used, it might lead to issues in the case of a weak internet connection. However, some software has already started to provide offline access so that it can synchronise later when connected to the internet again (da Costa et al., 2024).

Requirement 2: Traceability Mechanisms

Traceability in the distribution step is necessary to maintain clear records of each action and actor involved in the journey of food products in case of food safety and quality concerns and food recalls, so that the actors can trace upward and track downward through all points of custody in accordance with the regulations and quality standards (Bosona & Gebresenbet, 2013). In the context of distribution, this requirement is necessary to create accountability for order fulfilment and preventive measures (Razak et al., 2023). Additionally, traceability mechanisms help distributors manage returns and reduce costs associated with reverse logistics (Razak et al., 2023). As food products pass through multiple handlers in the distribution step, keeping track of each party involved might be challenging due to the complexity of the stakeholder networks. This is especially challenging when traceability data is heterogeneous due to the lack of standards in traceability systems and reluctance in data sharing or cooperation between the actors, which can hinder transparency efforts (Gallo et al., 2021). Another challenge here could be the possibility of human error in accurate data entry, such as failure to properly update inventory or record-handling data (Lao et al., 2012).

The decentralised structure of blockchain technology (BCT), in combination with smart contracts, would be suitable for operating in a complex chain of custody while increasing the accountability of the actors through immutable records of transactions (A. K. Singh & Raza, 2023). Furthermore, using automated data collection tools (e.g. RFID tags, barcodes, and QR codes) can simplify the tasks for each actor while reducing the risk of human error (Panos & Freed, 2007). Another solution to reduce the risk of human error in data entry would be AI-assisted data entry for error checks and validation (Tsolakis et al., 2023). To bring more consistency to the distribution network and reduce its complexity, the use of supplier compliance programs can make it easier to communicate and collaborate for better integration (Cascone et al., n.d.). Encouraging the actors to adopt a standardised framework for internal and external traceability could also be useful for better data integration and consistency (Latino et al., 2022). In addition, the actors can connect different technology systems within the cloud

via integration platforms as a service (iPaaS) (Jagtap et al., 2021). There could be other relevant challenges and matching technology solutions identified in relation to the traceability efforts in the distribution step, which can be found in the discussion on the transportation step.

Requirement 3: Order Accuracy and Fulfilment Tracking

Ensuring order accuracy and fulfilment tracking is a critical requirement to create transparency in the distribution step since order fulfilment is the most central activity, and it is strongly linked to continuous real-time data collection (Jagtap et al., 2021). The main focus of this requirement is to build and maintain trust between the business partners and improve operations efficiency (Bumblauskas et al., 2020; Vlachos & Bourlakis, 2006). Retailers and other buyers demand assurance that the correct products are delivered in the expected condition in the right quantities, which requires the monitoring of each step of the order process (Rábade & Alfaro, 2006). Maintaining accurate records of the order process also affects the correct consolidation and deconsolidation of goods, which is significant for preventing food losses (Jedermann et al., 2014). A common challenge that hinders the successful execution of this requirement would be the reliance on manual processes and resulting human errors, as well as the lack of real-time data integration (Lao et al., 2012). These challenges get more severe when the technology infrastructure is insufficient or outdated (Scholten et al., 2016). Ineffective communication and coordination between the actors in this step can also lead to order fulfilment errors, and this challenge is often exacerbated in larger distribution networks (Bosona & Gebresenbet, 2013; Helm et al., 2024).

To address the transparency challenges in order accuracy and fulfilment tracking, the actors can upgrade their infrastructure by investing in warehouse management systems (WMS) to optimise all aspects of warehouse operations (Maulana et al., 2021) or integrate enterprise resource planning (ERP) interfaces to ensure all components of distribution seamlessly work together (Anggara et al., 2024). Automating the key processes could be an effective way to minimise human error, and this can be in the form of material handling of arriving products, sorting, quality monitoring, packaging, and palletising (Jagtap et al., 2021). Another technology solution would be the use of voice recognition technology that allows warehouse employees to receive instructions both to reduce human error and improve operations efficiency (Berger & Ludwig, 2007). Since it would be difficult to achieve this requirement without data integration, the actors would need to adopt suitable technology solutions, such as API integration (Dave & Mittapally, 2024) and cloud-based platforms (Goldstein et al., 2022). Language and cultural barriers might be one of the reasons for ineffective communication issues in large and global distribution networks, which can be tackled by multilanguage communication tools (Ozturk, 2024)

Requirement 4: Compliance Tracking and Reporting

This requirement is concerned with ensuring that all activities executed within the distribution step are compliant with relevant regulations and quality standards. Ensuring compliance is vital to continuing the distribution operations, and it is also one of the main ways to create transparency. In the complex structure of distribution networks that cover various regulatory landscapes, making the right arrangements to track compliance is necessary for the actors in this step to safeguard public health and avoid legal consequences (Marucheck et al., 2011). Achieving this requirement is also linked to providing quality assurance and maintaining consumer trust (Kotsanopoulos & Arvanitoyannis, 2017). In the context of distribution, ensuring compliance allows distributors to effectively and legally allocate products across different markets. Since consolidation and deconsolidation can involve changing the packaging or the products themselves, they might be subject to regulatory compliance (Cheng & Tsai, 2009). This is also linked to the customisation of the products in different regions, which requires meeting specific local regulatory requirements and standards (Grigoriou, 2013). However, there might be some challenges related to compliance tracking and reporting, such as the complexity of regulatory environments of distribution networks (Chatzopoulou, 2015) and the integration of compliance data across systems (Accorsi et al., 2018). Similar to the challenges in the previous sections, cost considerations and potential data security and privacy issues can be considered relevant for this requirement as well.

Regulatory compliance appears to be a significant requirement for many FSC steps, and even though the contexts are different, the challenges and matching technology solutions seem to be similar, as can be seen in the previous FSC steps. Therefore, these connections are covered briefly in this section. Regarding the complexity of compliance, the actors might benefit from regulatory technology (RegTech) (J. Li et al., 2023), AI and ML tools (Padmanaban, 2024), and compliance databases and management systems (Längle et al., 2024). For the integration of compliance data across distribution networks, ERP systems with specialised compliance modules (Debreceny et al., 2005) could be a viable option, along with API and middleware integration (Dave & Mittapally, 2024), and blockchain technology (BCT) (Cao, Xu, et al., 2023). To reduce costs, the actors can choose cloud-based compliance solutions (Kassahun et al., 2014). Finally, the actors can improve data security and privacy via advanced encryption methods, data access control systems, or secure blockchain platforms (Tanwar et al., 2022).

Requirement 5: Cross-Partner Communication and Data Sharing

Due to the involvement of various business partners in distribution networks, effective communication and seamless data sharing among all partners are necessary because creating

transparency in this step requires an integrated system where all partners can access the same data relevant to their operations (Akkerman et al., 2010). Failure to achieve this requirement results in data gaps, and the operations would not be synchronised, which can lead to inefficiencies, miscommunication, misunderstanding, and possible damage to the trust among partners (Dania et al., 2018). Regarding the unique characteristics of the distribution step, transparency in data sharing allows synchronisation of supply and demand for better market matching (Wadhwa et al., 2010). It is also linked to horizontal logistics collaboration for better order fulfilment (Yuan et al., 2019). Some of the challenges that need to be addressed would be insufficient technological infrastructure for data sharing (Scholten et al., 2016), the lack of data standardisation, and the reluctance to share data (Gallo et al., 2021).

Insufficient technological infrastructure appears to be a critical challenge that is repeatedly encountered in other requirements and other FSC steps. As previously discussed, cloud-based services for data sharing are viable options by offering sophisticated IT infrastructures on a subscription basis and reducing the need for big initial investments (Kassahun et al., 2014). Even though it is not a technology solution, building public-private partnerships (PPPs) is an important and sometimes necessary solution to ensure all actors have the necessary resources for effective communication and data sharing (Eruaga, 2024). Once the actors have access to the necessary tools for data sharing, they should also address the data standardisation issues. One of the possible solutions is to build centralised data management systems within the distribution network (Kassahun et al., 2014). However, this solution would work when the network involves a high level of trust among business partners or a regulatory mandate (Kassahun et al., 2014). Another solution would be implementing data standardisation protocols for consistency and easy interpretation of shared data (Keogh et al., 2020). For less-structured distribution networks, integrating middleware solutions could be suitable to bridge different software and databases, which helps to standardise and translate data into a common format (Dave & Mittapally, 2024). Oftentimes, the partners are reluctant to share data with each other because of confidentiality and competitive advantage concerns (Krumpholz et al., 2021). This issue can be addressed by the use of data encryption (Tanwar et al., 2022) and defining strict access controls (Kaushal et al., 2024). It is also important to have transparent discussions on specifying data governance structures for data sharing and to prepare mutual benefit agreements accordingly, which can be facilitated with smart contracts in complex supply chains (Silvestri et al., 2024).

Requirement	Importance	Challenge	Technology Solution
Real-time inventory	Order fulfilment, delays, order errors,	Fragmented systems and data silos, cost of	IoT devices, cloud-based ERP systems, API integration, middleware solutions,

tracking and environmental condition monitoring	food waste, market matching, inventory management, food safety and quality, public health risks, non-compliance, and brand reputation	implementation, lack of technological infrastructure, and technical issues	AI, ML, low-cost sensor technologies, renting IoT equipment, open-source platforms, pay-as-you-go pricing models, cloud-based systems, modular IoT solutions, predictive analytics and maintenance tools, and software with offline access
Traceability mechanisms	Food safety and quality, recalls, compliance with regulations and quality standards, accountability, order fulfilment, preventive measures, and managing reverse logistics	Complexity of distribution networks, heterogeneous data (lack of standards, reluctance to share data and cooperate), and human error in data entry	BCT, smart contracts, automated data collection tools (e.g. RFID tags, barcodes, and QR codes), AI-assisted data entry, supplier compliance programs, standardised traceability framework, and cloud-based iPaaS
Order accuracy and fulfilment tracking	Order fulfilment, trust, operations efficiency, consolidation and deconsolidation of goods, and food waste	Manual processes and human errors, lack of real-time data integration, inadequate technology infrastructure, and poor communication and coordination	WMS, ERP systems, automating key processes, voice recognition technology, API integration, integrated cloud-based platforms, and multilanguage communication tools
Compliance tracking and reporting	Public health, legal consequences, operational efficiency, quality assurance, consumer trust, product allocation, consolidation and deconsolidation, and customisation	Complexity of regulatory environments, integration of compliance data across systems, cost of compliance infrastructure, and data security and privacy issues	RegTech platforms, AI and ML tools, compliance databases and management systems, ERP systems with compliance modules, API integration, middleware solutions, BCT, cloud-based compliance solutions, advanced encryption methods, data access control systems, and secure blockchain platforms
Cross-partner communication and data sharing	Synchronisation, operational efficiency, reducing data gaps and miscommunication, trust among partners, and market matching	Insufficient technological infrastructure for data sharing, the lack of standardisation, and the reluctance to share data	Cloud-based services based on subscription, building PPTs, centralised data management systems, data standardisation protocols, middleware solutions, data encryption and access controls, and mutual benefit

			agreements facilitated by smart contracts

Table 4. Connections within the distribution step

2.1.5 Retail

The D2.1 report refers to retail as synonymous with the consumer channel, and it is defined as a broad term that encompasses any outlet providing the final food products to the consumer. The most commonly identified retailers in the report are supermarkets, and other examples are listed as hotels, restaurants, or even school cafeterias. Key activities in the retail step can be generalised as procurement, storage, handling, display, promotion, sales, and customer service (Hübner et al., 2013). Ensuring continuous accessibility of food products in expected quality and price levels while preventing any food safety issues are the key concerns in the retail step (Srivastava et al., 2015). According to the D2.1 report, retailers are often the drivers of transparency interests in FSCs due to regulatory requirements, certification and labelling standards, protecting the brand image, and pressures from NGOs. Another key reason for their transparency interests is building and maintaining consumer trust, which can be realised through providing information on certifications as well as on food attributes, product origin, and traceability (W. Wu et al., 2021). As consumers are increasingly concerned with the sustainability of the food products they purchase, some retailers can rely on transparency to communicate their commitment to sustainability (Ehgartner, 2018). Furthermore, the demand for sustainability often involves demands for ethical behaviour and more transparency, which makes it difficult to be more sustainable without being more transparent (Ehgartner, 2018). While the examples given so far mostly refer to the main reasons for the retailers to create transparency, they also need to receive transparency from their business partners to be confident in their claims as well as manage risks for the resilience of their supply chains (Chu & Pham, 2022). This is especially important as consumers and policymakers tend to consider retailers responsible for the integrity of food products (Donaldson, 2022). However, being the driving actor of transparency initiatives could also be motivated by having more control over the supply chain, as discussed in the D2.1 report.

Connections Between Requirements, Challenges, and Technology Solutions

Requirement 1: Accurate and Complete Product Labelling

Ensuring the labels of the food products are clear, accurate, and complete is a non-negotiable requirement for retailers because from the consumers' perspective, it is the most functional way to obtain relevant information (Lam et al., 2020; Neitzel, 2020). In most cases, consumers rely on labels to make informed decisions, and inaccurate or incomplete labels might lead to serious consequences,

such as health issues (due to inaccurate information on allergens and expiration dates), consumer distrust (due to food safety and quality issues), and legal liabilities (Kuchler et al., 2017). Additionally, labels are the spaces where food products can be distinguished from competitor brands and important elements of marketing activities in retail (Górska-Warsewicz et al., 2018). However, these considerations come with their own challenges to address. For instance, retailers often rely on the actors in the previous FSC steps for product information, and it is challenging to ensure that the data they receive is trustworthy (Donaldson, 2022). Another challenge would be complying with frequently changing labelling regulations in different regulatory environments in which they operate (Trienekens & Zuurbier, 2008). Retailers also need the limited space on product labels to be optimised so that they can meet the increasing demands for more transparency, such as sustainability-related information (Van Loo, 2016).

As retailers do not generate the product information they put on the labels, they need to ensure the accuracy and integrity of the data they receive from their business partners. One possible solution is to enforce the integration of automated data entry tools to reduce human error and fraudulent behaviour risks (Feng Tian, 2017; Panos & Freed, 2007). These tools can be accompanied by ML algorithms to cross-check the data against multiple datasets for verification (Stoitsis et al., 2023). The existence of a centralised product information management (PIM) system for these data would support the retailers to consolidate and standardise the data and automatically check for inconsistencies and inaccuracies (Pencheva, 2021). As an additional measure, the use of blockchain technology (BCT) could improve the integrity of the data by reducing the risk of fraudulent behaviour thanks to its tamper-proof features (Feng Tian, 2017). To reduce regulatory compliance complexity, retailers can use regulatory compliance software for automatic updates on regulation changes and to meet specific regional regulatory requirements (Kotsanopoulos & Arvanitoyannis, 2017). Implementing AI-powered labelling audits could be another solution to adapt the labels to regional regulations through automated audits on the labels (Chhetri, 2024). The issue of limited space on the labels can be tackled by using QR codes and smart labels to link the product to digital content (Tanner et al., 2019). Retailers can also benefit from their websites and mobile apps to create digital product catalogues to provide detailed information on the food products and receive key insights on consumer engagement via the built-in monitoring features (Benthem De Grave et al., 2024). Another solution would be using AR applications to allow consumers to scan the labels and view the digital product information in an interactive way (Chiu et al., 2021).

Requirement 2: Traceability Systems

Similar to the previous FSC steps, traceability is a crucial requirement to create transparency in the retail step and for this requirement to effectively create transparency in this step, it has to be properly integrated in the previous steps. Consequently, retailers are required to ensure that traceability systems are in place within the operations of their business partners so that they can track the movement of the goods they sell from the farms to the shelves (Donaldson, 2022). For retailers, traceability is essential for verifying the safety and quality of food products, and without it, they might not be able to manage their supply chain, face legal consequences, and damage consumer trust and brand reputation (Azevedo et al., 2023). The challenges to achieving a trustable traceability system are also similar to those in the previous steps. In the context of retailers, integration across multiple systems is a significant challenge as they have numerous business partners, each with different traceability systems (Engelseth, 2009; Ringsberg, 2014). Retailers also need to maintain the consistency and accuracy of the data within their complex traceability systems, which can be challenging due to manual data entry and different data standards (Bhatt & Zhang, 2013). Some small and remote suppliers may lack the technological infrastructure to meet the retailer's traceability demands (Bachev, 2012), and this is a significant issue for the retailer because they would have to deal with the data gaps due to this barrier.

To create a unified traceability network, API-based integration platforms could be beneficial as they can allow different traceability systems to communicate seamlessly (Dave & Mittapally, 2024). Cloud-based traceability solutions are also promising for integration across the supply chain because they can be easily accessed by and integrated with existing systems (Islam, Manning, et al., 2021). Retailers can also adopt supply chain management (SCM) software to integrate traceability functions with other supply chain steps (Haulder et al., 2019; Kumar et al., 2020). For data management issues, establishing a data governance framework could support retailers to outline clear standards for data entry, management, and sharing (Latino et al., 2022). Another solution could be the implementation of ML algorithms for data standardisation across suppliers (Zeb et al., 2021). This way, inconsistencies can be detected and corrected to ensure a unified data management system. Regarding the technological barriers, retailers, as the drivers of traceability efforts in their supply chains, can support their smaller suppliers to deploy IoT devices that can be integrated with larger traceability systems. This can be achieved through partnerships with technology providers to offer subsidised traceability solutions to small-sized suppliers tailored to their needs and capabilities. Retailers can also develop mobile-based traceability applications that allow their small-scale suppliers to input traceability data by using their smartphones with minimal technical expertise and financial costs (Chen et al., 2020).

Requirement 3: Real-Time Inventory Management

Retailers need to have real-time data to monitor their stock levels as well as product turnover and expiration dates (Bottani et al., 2017). Failing to achieve this requirement causes understocking or overstocking of the inventory, which can lead to consumer complaints, food waste, financial loss, and inefficient and unsustainable retail operations (Ikpe & Shamsuddoha, 2024). The transparency created with this requirement is focused on the availability of food products, and it has a supportive role in realising other requirements in the retail step. However, there are some challenges that might hinder the successful realisation of this requirement. In the context of retail operations, real-time monitoring and tracking of the expiration dates of perishable food products with short shelf lives is especially crucial, but it could also be challenging when dealing with large inventory volumes (Grunow & Piramuthu, 2013). Another possible issue would be synchronising and managing inventory across all retail locations and online platforms (Pereira & Frazzon, 2021). In addition, implementing real-time inventory management systems could be costly for some retailers, particularly smaller ones (Ahmad & Zabri, 2016).

It is not very likely to manage real-time monitoring and tracking of the shelf life of perishable goods without the installation of IoT devices, and RFID tags, in particular, are widely used in smart inventory management (Sallam et al., 2023). For more sophisticated solutions, retailers might consider integrating AI-powered predictive analytics into real-time perishable item data (e.g., historical data, environmental conditions, and handling data) to optimise stock rotation and reduce food waste (Şimşek, 2024). By using dynamic pricing algorithms, retailers can adjust their prices based on the remaining shelf life for faster turnover (Kayikci et al., 2022). Regarding the data synchronisation issues, retailers can automatically update inventory data via blockchain-supported smart inventory solutions that would sync the inventory across channels where all relevant partners have access to the same information (Mondol, 2021). Retailers can also integrate collaborative supply chain management (SCM) tools that consolidate data from multiple sources, which can reduce data mismatches and improve inventory accuracy (Rubiano Ovalle & Crespo Marquez, 2003). If managing real-time inventory proves to be costly, there are possible technology solutions to lower the costs. Since such cost-reducing solutions were also introduced in the previous sections, those relevant to the retail step can be summarised as cloud-based inventory solutions (Lu & Wang, 2016) and pay-per-use IoT solutions (Sallam et al., 2023).

Requirement 4: Supplier Transparency and Collaboration

In their complex network consisting of various suppliers, retailers rely on the data they receive from their suppliers, and their success depends on the transparency of these actors. This transparency may

include information on sourcing practices, production and handling methods, and sustainability measures (Cao, Johnson, et al., 2023). Without this transparency, retailers cannot provide a guarantee to the consumers about the safety, quality, and sustainability of their products, and they cannot manage the risks against disruptions (Akram et al., 2024). Especially with the introduction of new regulations keeping retailers responsible for the actions of their suppliers (e.g. EU Directive on Corporate Sustainability Due Diligence)[3], ensuring this transparency will be legally enforced on retailers soon (Rao et al., 2024). However, there are some possible barriers that might prevent or hinder the creation of supplier transparency and collaboration. For instance, suppliers may be reluctant to share detailed information due to the fear of revealing business secrets and losing competitive advantage (Krumpholz et al., 2021). Moreover, transparency efforts might further exacerbate the inequalities among suppliers when the process leads to the abandonment of suppliers with fewer resources to meet the transparency requirements of the retailers (Searcy et al., 2022). Even when they share information, it might not lead to enhanced transparency if there is a lack of standardisation in the data retailers receive (Mol, 2015). The global and complex characteristics of the retail network would be another challenge, as tracking and verifying information across the chain can get very resource-intensive (Akkerman et al., 2010).

To reduce supplier reluctance to share information and collaborate, retailers can utilise permissioned blockchain platforms where suppliers can control access to the data they share, creating trust within the network (H. Wu et al., 2019). Using smart contracts to enforce confidentiality agreements is another possible solution to create trust, as the sensitive information is only shared with authorised parties (Wang et al., 2021). Since this process is executed automatically based on pre-defined conditions, it can reduce the reluctance to disclose information. Retailers can also develop financial and non-financial incentive schemes that foster inter-firm collaboration for the added value of information sharing (Zipfel et al., 2020). Such collaborations can also be beneficial in improving the integration of global data standards (such as GS1) into their supply chains through joint workshops, shared platforms, and regular data-sharing reviews (Semianiaka & Silina, 2012). Another solution would be using industrial data platforms for certification data that incorporate encryption and authorisation to facilitate data sharing according to supported data standards (Papageorgopoulos et al., 2022). In the context of global and complex supply chains, AI-driven solutions can enable retailers to navigate the complexities and gain more visibility by identifying complex patterns and generating actionable insights (Nimmagadda, 2023). Such tools can also support retailers with risk assessments

[3] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401760

through monitoring and identifying transparency gaps to get recommendations on possible mitigation strategies.

Requirement 5: Compliance with Food Safety Standards

Like all FSC actors, retailers must adhere to food safety standards on proper storage, handling, and sanitation, which results in enhanced transparency in the chain (Eruaga, 2024). In this context, the main goal of the transparency efforts is linked to fostering trust and collaboration to prevent food safety incidents and protect public health (Eruaga, 2024). Additionally, there is a risk of facing legal consequences and damage to brand reputation in case of incompliance (Azevedo et al., 2023). In the context of retailers, they need to ensure the compliance of the actors in their network in addition to their own compliance (Minor et al., 2019). However, ensuring that these standards are consistently met across wide retail networks is a challenge, and another layer of complexity is added due to diverse and frequently changing regional regulations (Kotsanopoulos & Arvanitoyannis, 2017). Furthermore, governments in some countries have decided to reduce budgets for inspections and monitoring, leaving the responsibility to the industry, which is considered by some retailers as an extra burden to monitor food safety (Fulponi, 2006).

To achieve consistency in compliance across retail networks, retailers can integrate blockchain technology (BCT) with global food safety standards and verify that all retail partners follow the same food safety protocols across the network (Keogh et al., 2020). Retailers can also implement e-learning and training platforms to ensure all staff are knowledgeable about the latest updates on food safety standards (Neal Jr et al., 2011). To reduce the complexity of compliance with diverse and changing food safety regulations, integrating automated regulatory tracking systems that utilise regulatory intelligence tools would be beneficial as they can provide real-time updates on new developments in the standards (Eltabey, 2023). Additionally, the retailers can use real-time compliance monitoring tools that are connected to a digital dashboard to receive reports on the compliance of their organisation. (Eltabey, 2023). If retailers wish to improve their level of preparedness, AI-driven predictive analytics could be an option to anticipate possible food safety issues and take proactive measures to ensure compliance (Friedlander & Zoellner, 2020).

Requirement	Importance	Challenge	Technology Solution
Accurate and complete product labelling	Informed decision-making for consumers, public health, consumer trust, legal	Receiving trustworthy data (data integrity and accuracy), frequently changing labelling regulations, and limited	Automated data entry tools, ML algorithms, centralised PIM system, BCT, regulatory compliance software, AI-powered labelling audits, QR codes

	obligations, competitive advantage, and marketing	space on labels for increasing transparency demands	and smart labels, digital product catalogues, and AR applications
Traceability systems	Food safety, quality, and authenticity, FSC management, legal obligations, consumer trust, and brand reputation	Integration across multiple systems, data accuracy and consistency, manual data entry, different data standards, lack of technological infrastructure, and data gaps	API-based integration platforms, cloud-based traceability solutions, SCM software, data governance frameworks, ML for data standardisation, low-cost IoT devices, partnering with technology providers, and mobile-based traceability application
Real-time inventory management	Product availability, efficient and sustainable operations, avoiding understocking, overstocking, food waste, and financial loss	Perishability and shelf life monitoring, large inventory volumes, data synchronisation issues, and high cost of implementation	IoT sensors, AI-powered predictive analytics, dynamic pricing algorithms, blockchain-supported smart inventory solutions, collaborative SCM tools, cloud-based inventory solutions, and pay-per-use IoT solutions
Supplier transparency and collaboration	Food safety and quality, sustainability, risk management, and legal obligations	Supplier reluctance to share information, lack of standardisation, global and complex retail networks	Permissioned blockchain platforms, confidentiality agreements via smart contracts, incentivised transparency programs, integration of global data standards, industrial data platforms (encryption and authorisation), and AI-driven analysis and risk assessment tools
Compliance with food safety standards	Fostering trust and collaboration, food safety, public health, legal obligations, consumer trust, brand reputation, and network compliance	Consistent compliance across the network, diverse and changing regulations, and the burden of monitoring and enforcement due to the lack of government involvement	Integrating BCT with global food safety standards, e-learning and training platforms, automated regulatory tracking systems, real-time compliance monitoring tools, digital dashboards, and AI-driven predictive analytics

Table 5. Connections within the retail step

3. Conclusion

Creating transparency in the global and complex food supply chains (FSCs) depends on the ability to utilise the potential of digital technologies. Currently, there are many technology options that can be used to achieve this goal, each with its own unique benefits and challenges regarding transparency creation. The utilisation of these technologies is linked to the ability to understand the context where transparency is aimed to be created so that the optimal mix of suitable technologies can be integrated within that context. However, defining the context is not an easy task since various considerations can be included in the discussion. In general terms, the context of FSCs would include the stakeholders, processes, infrastructure, regulations, and external factors. This report presents the first version of the approach to creating digital transparency in FSCs in relation to potential requirements and cross-cutting challenges that can be identified. Here, requirements refer to the necessary capabilities of a system to create transparency, whereas challenges refer to the obstacles in achieving those capabilities.

As the context of FSCs can include various elements, this report starts the discussion on the approach based on FSC steps in relation to stakeholders. These steps are based on the list of stakeholders identified in the D2.1 report, and they are presented in this report as primary production, processing, transportation, distribution, and retail. The context of each of these steps shapes its unique set of requirements, and each requirement is discussed in connection with potential challenges that might arise to prevent or hinder the successful implementation of the requirement. For each challenge, there may be several possible technology options that can overcome the challenge, which can unlock transparency creation in FSCs. In other words, the connections between the requirements, challenges, and technology solutions lay the foundation of the approach, which aims to bring more structure to the complexities of transparency creation in FSCs and provide guidance for formulating transparency initiatives.

The content provided in this report on possible requirements, challenges, and technology solutions is given to set an example from a broad perspective, and the main goal here is to communicate a way to approach the complexity of transparency creation in FSCs. When applied to a specific case, these considerations might include different discussion points based on the unique context of that case. Moreover, the structure of the FSC of the case could also involve different FSC steps (as can be seen in the D2.1 report) when applying the approach to its context. It is also important to note that the discussion points included in this report are based on the most commonly encountered requirements and challenges and matching technology solutions in the literature. When considered in the context of a specific case, it is very likely to identify more requirements and challenges that are also more

context-specific. It might also be the case that some of the requirements and challenges listed in this report may not be relevant to all cases this approach will be applied, depending on the context. However, it is possible to identify unique requirements and challenges for the case in question by following how example connections are built in this approach.

3.1 Future Steps

Developing a context-based approach requires structure to systematically identify requirements and cross-cutting challenges, which is necessary to explore suitable technology solutions among various options. Starting the discussion on FSC steps and relevant stakeholders has built the foundation of the approach by demonstrating how different steps may have different contexts and how the same requirements, challenges, and technologies might be discussed from different perspectives due to contextual differences. In this regard, the context of FSC steps also involves different stakeholder motivations to create transparency. From this starting point, more layers will be added to the approach in connection to other possible elements of the context, such as the data flow structures, types of data shared among the actors, the influence of other stakeholders (such as the secondary stakeholders identified in the D2.1 report), and more detailed examination of possible technology solutions including their unique benefits and challenges. The Appendix provides more information on the possible organisation of the data that will be collected from the TITAN pilots during the next steps of the approach.

The next step will be applying the approach to the specific context of the selected TITAN pilot beneficiaries, and it will be further developed through iterative sessions with the pilots until there is consensus on the sufficiency of the approach in connection to its ability to enhance transparency in their context. In this regard, the approach will be built upon the BPMN models created for the TITAN pilots in the D3.1 report. As a result, the context of each pilot will represent a case study, which can provide practical information to other food sector actors and policymakers in relation to the evaluation of digital technologies for transparency. To bring more structure to the approach, a framework will be developed to position the elements of the context in a way that provides practical guidance for transparency creation. This may be in the form of guiding questions, principles for coupling opportunities, or process patterns.

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List of Tables

Table 1. Connections within the primary production step 18
Table 2. Connections within the processing step 25
Table 3. Connections within the transportation step 32
Table 4. Connections within the distribution step 39
Table 5. Connections within the retail step 45

Appendix

This appendix includes possible ways to organize data that will be collected from the TITAN pilots when applying the approach to their specific context. The purpose is to reduce the complexity of the context and make the task of finding the right technology mix easier. The elements of the tables below will be identified by the pilots and they will be elaborated through iterative sessions. After sufficient data is collected, the tables will be used to create the framework as the final version of the approach, which can be in the form of patterns or guidelines for digital transparency creation.

	FSC step-1	FSC step-2	FSC step-3	FSC step-4	FSC step-5
Data collection	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology
Data preparation	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology
Data storage	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology
Data sharing	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology
Data disposal	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology
Data security and privacy	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology	Requirement Challenge Technology

Table 6. Example identification of the requirements, challenges, and possible technology solutions in data lifecycle steps in the context of each FSC step

	Requirement-1	Requirement-2	Requirement-3	Requirement-4	Requirement-5
Technology option-1	+	-	+	+	-
Technology option-2	-	-	+	+	-
Technology option-3	+	+	+	+	-

Technology option-4	-	-	+	-	+
Technology option-5	+	-	+	+	+
Technology option-6	-	+	-	-	-

Table 7. Example classification of different technology options

	Technology option-1	**Technology option-2**	**Technology option-3**	**Technology option-4**	**Technology option-5**	**Technology option-6**
Technology option-1		Requirement Challenge	Requirement Challenge	Requirement Challenge	Requirement Challenge	Requirement Challenge
Technology option-2	Requirement Challenge		Requirement Challenge	Requirement Challenge	Requirement Challenge	Requirement Challenge
Technology option-3	Requirement Challenge	Requirement Challenge		Requirement Challenge	Requirement Challenge	Requirement Challenge
Technology option-4	Requirement Challenge	Requirement Challenge	Requirement Challenge		Requirement Challenge	Requirement Challenge
Technology option-5	Requirement Challenge	Requirement Challenge	Requirement Challenge	Requirement Challenge		Requirement Challenge
Technology option-6	Requirement Challenge	Requirement Challenge	Requirement Challenge	Requirement Challenge	Requirement Challenge	

Table 8. Example identification of technology mix solutions in relation to requirements and challenges

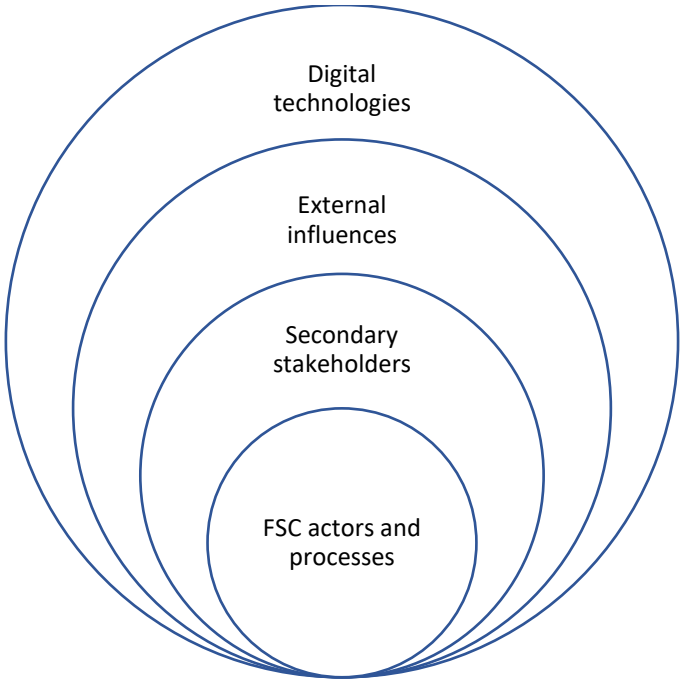

Figure 1. Example visualisation of the context of digital transparency in FSCs