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AI-Driven Digitalization in Finland's Waste management Sector: Enhancing Circular Economy through Sustainable Technological Innovation

Case Study Of Stormossen AB Oy

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ABSTRACT

This paper examines the role of Artificial Intelligence (AI)-based digitalization in the implementation of the Circular Economy (CE) in the waste management (WM) industry in Finland by applying the Socio-Technical Systems (STS) theory. The study is a qualitative single-case study of Stormossen one of the most successful Finnish companies in the waste management area- the study explores the relations between technological structures, organizational operations and adaptation of people. Semi-structured interviews, document analysis and observations were employed to collect the data that were analyzed through the six-phase thematic analysis of Braun and Clarke (2006).

The findings reveal eight interrelated themes: digital integration and tools, data collection and usage, organizational adaptation and learning, socio-technical interactions, CE outcomes, challenges and opportunities, and emerging AI potential. Results show that AI and digital tools enhance operational efficiency, traceability, and decision-making, while organizational learning and leadership foster socio-technical alignment. However, barriers such as data fragmentation, skill gaps, and limited policy integration constrain progress.

The contribution to the theory of the study, in turn, is the generalization of the Socio-Technical Systems theory to a sustainability and AI platform, with the focus on the joint optimization of human and technical systems. In practice, it provides a digitalization roadmap to waste management companies on their way to the circular model in accordance with the CE objectives of Finland.

KEYWORDS: AI, Socio-Technical Systems, Circular Economy, Digitalization, Waste Management, Finland.

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AI	Artificial Intelligence
CE	Circular Economy
IOT	Internet of Things
STS	Socio-Technical Systems

1 Introduction

The transition from a static economy based on a "take, make, dispose" model to a Circular Economy (CE) has become a cornerstone of sustainable development worldwide. circular economy promotes waste elimination, the circulation of materials, and the restoration of natural systems (Neves & Marques, 2022; González-Sánchez et al., 2023). Within this context, the waste management (WM) sector plays a pivotal role by conserving resources and reducing waste generation, thus supporting both environmental sustainability and industrial development (Reis et al., 2023).

In Finland, the principles of the circular economy are integrated with the national strategy of sustainability. The nation has been ranked among the world's pioneers in the application of CE, especially in waste management. Recycling has become 98-99% in areas like Ostrobothnia, which proves the high level of adherence to the EU Waste Framework Directive and the national goal of carbon neutrality of Finland by 2035 (Peura et al., 2022; Ministry of the Environment, 2021). An active culture of policy, infrastructure investments and sustainability-oriented culture contributes to this leadership (Sitra, 2016; Lazarevic et al., 2022). Nevertheless, further success of the CE transition in Finland also relies more on the incorporation of digital technologies. The Ministry of the Environment (2021) states that to make its waste-free circular economy, it is essential to have sophisticated digital innovations that increase traceability, transparency, and efficiency of the material cycles. The use of Artificial Intelligence (AI), the Internet of Things (IoT), and data analytics is emerging as an important element in streamlining the collection system, recycling, and recovery of resources (Peura et al., 2022). The current waste systems may be in danger of stagnation unless digital transformation occurs.

At the same time, the global population and the growth of urbanization still exert increasing pressure on the formation of waste. According to the projections made by the World Bank (2018), the level of municipal solid waste will grow by 2.01 billion tons in 2016 and rise to

3.40 billion tons by 2050, of which almost 70% of the growth will take place in urban regions. Post-consumption waste management usually gets overlooked in linear systems (Ellen MacArthur Foundation, 2013), resulting in environmental high pollution, emission of greenhouse gases, and health hazards (Siddiqua et al., 2022). These challenges are particularly acute in low- and middle-income countries, where waste collection efficiency remains below 50% of that in high-income economies (Zhang et al., 2024). Digitalization, such as AI, presents the possibilities to deal with such issues. The combination of such tools as predictive analytics, sensor-based monitoring, and decision-support dashboards allows waste management companies to maximize operations and promote CE objectives. As an example, global route optimization and robotic sorting can cut down logistics expenses by more than 13% and have a high classification rate (Fang et al., 2023).

Digital transformation is already transforming waste management in Finland. Companies such as Stormossen, located in Vaasa, have implemented IoT-enabled tracking systems, automated logistics, and digital service platforms such as Materiaalitori, which connects waste producers with potential users (Motiva, 2024). These processes indicate that the country is prepared to be CE-oriented in terms of innovations. Nevertheless, technological advancement is observable, but the social and organizational aspects of readiness of the employees, inter-organizational cooperation, and the culture of learning are less clear (Chen and Wang, 2024).

Despite the growing interest in digital innovations, including AI, there is a lack of research on how digital transformation supports the Circular Economy and waste management practices. Studies such as Ghoreishi and Happonen (2020) emphasize efficiency improvements while neglecting broader supporting outcomes such as resource cycles, collaboration, and process change. Similarly, Peru et al., (2022) highlight the need for research on how digital tools, including emerging AI applications, can enable CE-focused business models and operational practices. In Finland, promising developments have emerged. Peura et al., (2022) record the development of the waste system of the Vaasa region, which shifted to products-service systems out of a one-bag throw-away culture, thus showing the changes in institutions, technology, and culture needed. International cases like AI-aided robotics and sorting with sensors indicate that they have improved operational efficiency and lowered landfill waste (Fang et al., 2023). However, still challenges, including the insufficient quality of data, high costs of implementation, and the barriers to digital readiness that are typically associated with the infrastructure, the skills of the workforce, and the organizational culture (Neri et al., 2024). Such impediments are especially essential in such a country as Finland, which is characterized by sustainable development. Once the high-tech companies cannot introduce digital tools, such as AI, to their further education, it is a problem of social change, the alignment of technology, people, and processes. Despite research on these changes, limitations persist that hinder both academic understanding and management guidance.

1.2 Research problem and theoretical contribution

This study seeks to address the gap by investigating the role of digitalization, including AI, in advancing CE practices in Finland's waste management sector. The research is guided by the following main research question:

How does digitalization, including AI, contribute to circular economy practices in Finland's waste management sector? (Case study: Stormossen)

To explore this question, four sub-questions are posed:

1. **Technological implementation:** Which digital tools (e.g., AI, IoT, data analytics platforms) are applied at Stormossen, and how are they used in daily operations?
2. **Organizational effects:** How do these digital tools influence organizational processes, employee roles, and decision-making?
3. **Circular-economy outcomes:** In what ways do digital technologies enhance resource efficiency, recycling, and waste reduction?

4. **Socio-technical challenges:** What barriers and enablers affect the adoption of digital and AI-driven systems within the socio-technical context of Finnish waste management?

In line with these questions, the study pursues the following objectives:

1. Identify the key AI-based and digital tools currently used in Stormossen's waste-management operations.
2. Examine how digitalization influences organizational behavior, collaboration, and learning.
3. Assess how digital technologies contribute to recycling efficiency, resource reuse, and sustainable innovation.
4. Explore socio-technical challenges and opportunities shaping AI integration in the Finnish waste management sector.

In the theoretical contribution, this work contributes to the development and implementation of the Socio-Technical Systems (STS) framework, namely, to the application of the framework to AI-driven transitions to the circular economy. It shows that sustainable results are possible not only from technological progress but from the joint optimization of technical infrastructures and human capabilities within their institutional and policy context. The results indicate that AI-based digitalization can increase efficiency, innovation, and material circularity when it works in line with the CE roadmap and organizational preparedness of Finland. In doing so, the study provides a gap between theory and practice by presenting a hybrid model of AI-driven socio-technical alignment, which demonstrates how digital transformation can be an instrument of facilitating sustainable and inclusive waste management.

The overall aim of this study is to explore how AI-driven digitalization, within Finland's circular economy policy context, enhances sustainable waste management through socio-technical integration.

Theoretical Framework

The study is based on the Socio-Technical Systems (STS) theory, which posits that organizational performance depends on the joint optimization of technical subsystems (tools, processes, and infrastructure) and social subsystems (people, culture, and structure) rather than treating them separately (Trist & Bamforth, 1951). Originating from the Tavistock Institute's studies in the 1950s, STS highlights the need for technology and human systems to co-evolve to achieve efficiency, adaptability, and sustainability (Emery & Trist, 1960).

The digital tools encompassed in the technical subsystem of the waste-management context of Finland are IoT sensors, data-sharing platforms (e.g., Materiaalitori), and predictive analytics, whereas the social subsystem entails the practices of employees, leadership, and organizational culture in the context of the sustainability orientation of Finland (Sitra, 2016; Peura et al., 2022). The structure is consistent with the RQ2 (sensitiveness of digitalization to processes and behavior) and RQ4 (adoption challenges and opportunities), which allows considering the adaptation of the employees at Stormossen to the new technologies and the cultural change effects, facilitating the rise of CE-based innovation. The study expands the scope of the socio-technical dynamics of the CE transitions by incorporating the principles of the circular economy (Ellen MacArthur Foundation, 2013) with digitalization and the use of AI (Fang et al., 2023). It suggests AI as a digital enabler that integrates human and technical systems to address obstacles like low-quality data and insufficient preparedness, thereby enhancing the efficiency of recycling, sustainability performance, and waste minimization. In terms of management, socio-technical alignment needs to be guaranteed by means of workforce training, joint governance, and cultural preparedness. Enhancing digital capabilities and data-sharing competencies will lead to an increase in efficiency of operations and stakeholder interaction. The results may also be used by policymakers to create supportive frameworks for ethical and evidence-based innovation of the waste-management industries in Finland.

1.3 Thesis structure

Chapter 1 presents the background, research problem, objectives, research questions and the theoretical framework. It also sets the framework of AI-based digitalization in the waste-management industry of Finland and its ties to the circular economy. Chapter 2 examines the literature on Circular Economy, Digitalization and AI in waste management, the Socio-Technical Systems theory, and concludes with the suggested conceptual framework. Chapter 3 presents the research methodology (selection of cases, data-collection (p. interviews, data analysis of documents), and analysis). Chapter 4 provides empirical results of Stormossen and developed according to the research questions. Finally, Chapter 5 presents result in terms of theory, formulating implications on academia, industry, and policy, and delineating research limitation and directions of future studies.

2. LITERATURE REVIEW

2.1 Stream 1: CE in WASTE MANAGEMENT

2.1.1 Broadly about the topic (history, background)

The concept of the CE emerged as a direct response to the limitations of the traditional linear economy based on “take, make, dispose”. The Ellen MacArthur Foundation (2013) emphasizes that it is “a linear model of resource consumption that follows a ‘take-make-dispose’ pattern. Companies harvest and extract materials, use them to manufacture a product, and sell the product to a consumer who then discards it when it no longer serves its purpose.

Table 1 Comparison of Linear and CE Models.

Aspect	Linear Economy	Circular Economy
Resource Flow	Take-make-dispose (one-way)	Closed loop (reuse, recycle, recover)
Waste Management	Waste as end-product (landfill/incineration)	Waste as resource (minimal waste)
Economic Focus	Growth tied to resource extraction	Decoupled from finite resources; focuses on efficiency and innovation
Environmental Impact	High depletion and pollution	Reduced impact through sustainability
Examples	Single-use plastics, fast fashion	Refurbished electronics, sharing economy

By contrast, CE reimagines waste as a resource within closed-loop systems. Tracing back historically, intellectual origins of CE lie in the 1970s with intellectual influences of industrial ecology and ecological economics that emphasized on resource efficiency and design of closed-loop production systems. (Ghisellini et al., 2016) state that the foundations of the CE exist in ecological and environmental economics and industrial ecology, and the overall goal of the concept is the isolation of economic growth and environmental pressures. This shows the development of CE as a scientific model and a working plan towards sustainability.

The European Environment Agency (EEA, 2022) emphasizes the nature of the CE which points to the fact that it entails a transition not just to renewable energy and materials, but as separating economic growth and the consumption of finite resources, promoting long-term resilience, generating economic and business opportunities, and bringing environmental and social benefits. An alternative view of the CE is as a set of practices but also as a comprehensive reform of the production and consumption systems. The focus of the transformation of the CE is often on waste management. According to (González-Sánchez et al., (2023), the process of CE is described as recycling and reengineering, which can secure the value of the resources by denying the end-of-life of products, minimizing wastes, and enhancing the quality of products via methods like recycling, reuse, and upcycling. It relies on the principle of material balance, which is to regenerate the processes of nature, i.e. to reduce the amount of waste and pollution. The last twenty years show that the attitude to waste management has changed to be less waste-focused and more reuse-focused, recovery-focused, and recycling-focused, according to the EU Waste Framework Directive (2008/98/EC), waste management has become one of the leading principles.

Finland is considered a pioneer in the circular economy, aiming to become a world leader by 2025. Finland Innovation Fund Sitra (2016), declared that Finland was the first country in the world to prepare a national road map to a CE in 2016, under the leadership of Sitra. This roadmap, titled Leading the Cycle, outlined 64 practical measures involving municipalities, industries, and citizens. Further emphasizes by Sitra (2016), that “a CE maximizes the life cycle of products through reuse and recycling, prioritizes renewable resources, promotes service-based models over ownership, and enhances the efficient recovery of energy”. This leadership has been reaffirmed through subsequent programs. The Technology Industries of Finland (2021), state in their CE Programme that *“in 2035, Finland’s economic success is founded on a carbon-neutral CE society.”*

Similarly, Lazarevic et al., (2022) observe that *"Finland is an interesting case to study CE policy, as it developed the world's first CE roadmap in 2016 (Sitra)."* At the regional level, Peura et al., (2022) document how Vaasa's waste system, including the municipal company Stormossen, transformed from a *"one-bag throw-away culture"* into advanced product-service systems. This example illustrates why institutional reforms combined with technical innovation and cultural changes were the factors that facilitated CE practices and revealed that waste management is a technological and social change.

2.1.2 Definitions of Circular Economy

The CE is often framed as a transformative approach to decouple economic growth from finite resource use through strategies like reuse, recycling, and regeneration. The Ellen MacArthur Foundation (2013), defines CE as *"an industrial system that is restorative or regenerative by intention and design,"* emphasizing both technical cycles like recycling materials and biological cycles like composting to maintain resource value

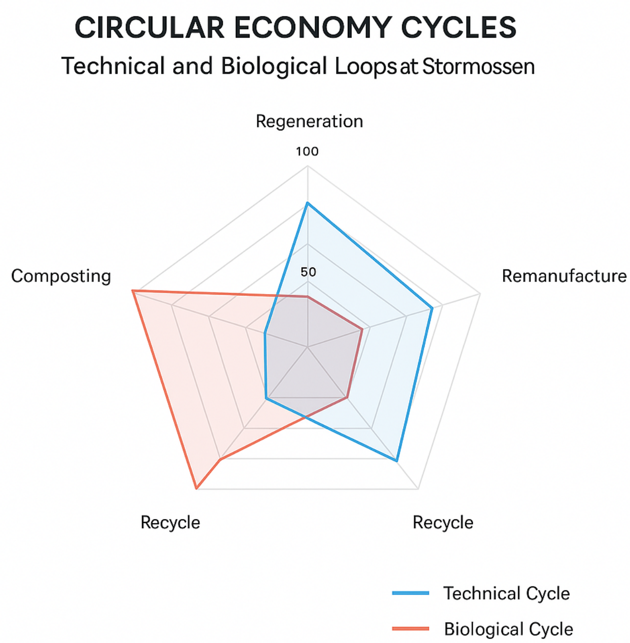

Figure 1 CE Cycles: Technical and Biological Loops at Stormossen

(Adapted Ellen MacArthur Foundation (2013))

This radar chart illustrates the dual cycles of the CE technical (reuse, remanufacture, recycle) and biological (composting, regeneration), showing how each contributes to resource value within Stormossen's waste-management system in Finland. The visualization is based on the circular-economy concept developed by the Ellen MacArthur Foundation (2013) and applied in the Finnish context (Government of Finland, 2021).

Likewise, according to the Government of Finland (2021), the CE is not all about recycling and is fundamentally re-evaluating the way materials, products, and services are designed and used. This framing links CE to Finland's national goals, such as the transition from a "one-bag throw-away culture" toward service-based business models. From an academic perspective, Kirchherr, Reike, and Hekkert (2017), define CE as an economic model that substitutes the notion of 'end-of-life' with practices of reduction, reuse, recycling, and material recovery throughout production, distribution, and consumption. Their review of 114 definitions highlights how recycling and recovery dominate CE discussions, though systemic change and cultural factors are less frequently addressed.

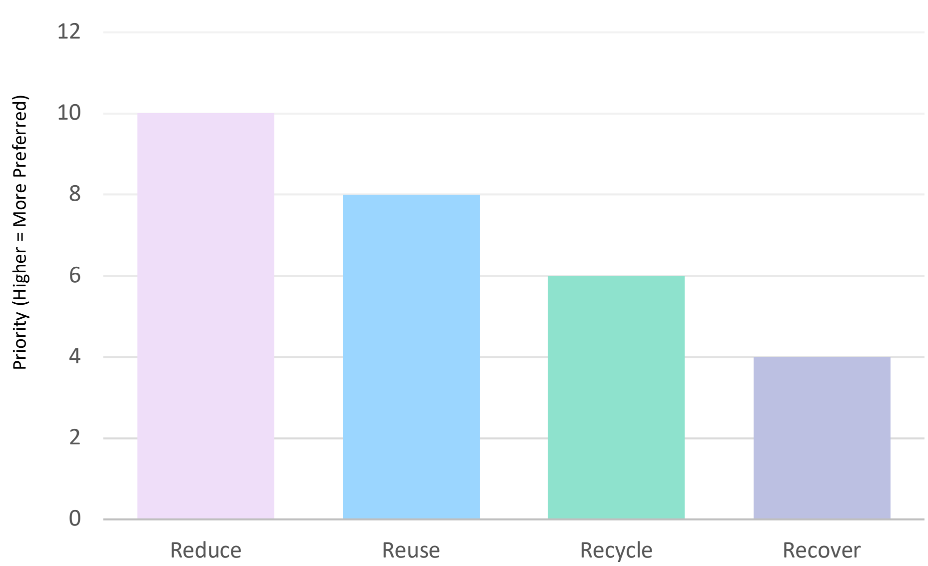

Figure 2 : The 4R framework priorities in the Circular Economy

(Adapted from European Environment Agency (2021) and the European Commission (2015),

As per this figure 2, the 4R framework focuses on minimizing waste development, and then reusing and recycling materials, and recovery. The 4R hierarchy is both outlined by the European Environment Agency (EEA, 2021) and the European Commission (2015) as one of the key elements of the European Union's waste prevention and circular economy policy. The hierarchy levels of reducing, reusing, recycling, and recovery are seen as reducing. Preventing the creation of waste by minimizing resource consumption; reusing: Stretching the life of a product by repairing or reusing; recycling: Reusing materials to create a new product; and recovery: Recovering materials or energy when neither of the above is possible. This is a qualitative priority as opposed to a numerical one, but commonly presented graphically (10, 8, 6, 4) to make the point of the decreasing preference among the 4Rs.

This framework can inform the analysis of the ways waste management practices can fit into a wider set of concepts of a circular economy. On this basis, Geissdoerfer et al., (2017) define the circular economy as a restorative system that decreases the use of resources, waste, emissions, and energy loss by extending, closing, and tightening material and energy cycles. Their definition singles out three interconnected processes of slowing, closing and tightening resource loops, which form the basis of circular strategies within systems of production and consumption. Nevertheless, the circular economy is a controversial and dynamic concept, despite its growing popularity. Korhonen, Nuur, Feldmann, and Birkie (2018), observe that the term is actively popularized among policymakers and business executives, but it does not have a clear conceptual understanding and consensus in practice.

This complexity highlights the need for organizations like Stormossen to view continuing education not as a system-focused change, but as part of a broader mix of digital innovation, behavioral change, and social integration with technology. This complexity highlights the need for organizations like Stormossen to understand continuing education not just as a collection of recycling or recovery practices, but as a holistic transformation, encompassing digital innovation, behavioral change, and social integration with technology.

Table 2 CE Research Categorization Matrix (Adapted from Korhonen et al., 2018)

Level of Research (Organizational Width)	Directly Observable	Not Directly Discernible
Individual/Organizational	Resource usage in processes; eco-efficiency metrics; waste generation in operations.	Organizational culture; strategic thinking; corporate social responsibility (CSR); intra-organizational learning.
Supply Chain/Network	Material/energy flows between organizations, renewable utilization in chains; life cycle assessments.	Collaboration culture; inter-organizational learning; sense of community in networks; capabilities for radical innovations.
Industry Cluster/Sector	Sector-wide footprints (e.g., emissions, resource consumption), industrial symbiosis tools.	Organizational inertia/resilience; cultural shifts toward sharing economy, governance and management structures.
Policy/Regional	Policy indicators for resource efficiency; regional waste-derived resource utilization.	Policy norms for sustainability; societal values on consumption; cultural adaptation to CE paradigms.
Global	Global material flow models; international emission reduction computations	Global worldviews on sustainable development; paradigmatic potential of CE vs linear economy cultural and ethical debates.

According to Table 2 (adapted from Korhonen et al., 2018), circular economy research can be categorized across two main dimensions: practical material flows and deeper societal or paradigmatic levels. This categorization helps to reveal research gaps particularly in understanding cultural, political, and social factors that influence the adoption of technologies such as artificial intelligence (AI) within organizations like Stormossen.

Explaining the political dimension, Valenzuela and Boehm (2017), suggest that, over the last few years, zero-waste and the circular economy discourses have been actively popularized by such influential groups as the European Commission, consulting agencies, NGOs, scholars, and multinationals. Although these accounts make the case of circular economy look like a potential sustainability solution, these discussions warn that such framing has the potential to depoliticize sustainability by asking it a question solely of technical or managerial concern. This threatens to hide the structural contradictions, inequalities and power relations underlying capitalist economies, as they observe. For example, the idea of a corporate program like Apple's zero-waste program is lauded, but it is based on the principle of sustainable consumer substitution, which demonstrates how the circular economy can support consumption-led growth. Developing this criticism, Corvellec et al., (2021) state that the concept of circular economy is not very clear and theoretically strong, with ambiguous boundaries and practical constraints. The chimeric concept of an ideal circle system ignores the basic rules of physics: waste and energy loss are inevitable. Despite the popularity of circular economy among policymakers and companies, its practical implementation is frequently limited, with much of it being a business-oriented and “win-win” approach to the problem instead of a social revolution.

In this context, the way in which the circular economy is defined in Finland, and particularly in Stormossen, depends on how digital and artificial intelligence are applied. A narrow, performance-focused approach to robotics or the Internet of Things emphasizes technological performance, while a broader, systems-based approach encourages collaboration, behavioral change, and cultural change. This highlights the importance of the Systems-Technology approach, which recognizes that successful circular change requires the integration of both technological innovation and human and organizational change.

2.1.3 Processes and Mechanisms of CE in Waste Management

The application of a circular economy model to waste management is based on diverse processes and procedures aimed at converting waste streams into valuable products, which would mitigate the level of environmental impact and enhance the efficiency of resources. In fact, the main waste streams serve as a foundation, which was first established in the EU Waste Framework Directive (2008/98/EC). This Directive establishes a guideline for waste management practices to ensure sustainability. According to what is mentioned in the Directive, the following waste streams will be included in the waste prevention priorities in regulatory and policy measures: (a) prevention; (b) recycling encouragement; (c) recycling; (d) other forms of recovery like energy recovery; and (e) disposal (European Parliament and Council, 2008, Article 4). Developing this, there are three interrelated loops to conceptualize circular economy processes: closing, slowing, and narrowing according to Geissdoerfer et al.,(2017), circular economy is a restorative system, which reduces resource consumption, waste, emissions, and wasted energy by lengthening closing, and tightening the material and energy flows offered by strategies such as durable design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling specifically.

The three major strategies to the concept of circular economy practice include closing resource loops, slowing resource loops, and narrowing resource loops. Closing loops The term closing loops describes the process of utilizing end-of-life materials in production processes by recycling or up-cycling to create closed material flows. Slowing loops aims at maximizing the life of the products and materials using those activities that increase the life of the product or materials, like repair, reuse, and remanufacturing that will lessen the extraction of new resources. Meanwhile, narrowing loops is expected to enhance efficiency, reduce the number of resources and energy used to produce a unit of output by improving the processes and optimizing the design. Combined, these measures become the basis of the thought of the circular economy by minimizing waste and ensuring sustainable use of resources.

These loops provide a dynamic framework for evaluating and implementing circular practices, emphasizing systemic change over linear disposal. This integrated approach is visually represented in Figure 4, which combines the waste hierarchy with circular economy resource loops. The recycling process is the circular economy, waste management backbone, which is the major connection between generating waste and recovering resources. According to Kirchherr et al., (2017) a circular economy is described as the economic approach in which business is not based on the traditional approach of end-of-life and is rather a business that is aimed at reducing, reusing, recycling, and recovering materials used in manufacture, distribution, and consumption.

The example of Stormossen operating in the Vaasa area of Finland is one where integrated sorting and recovery systems have achieved recycling rates of 98-99%. Peura et al., (2022) note that the institutional and technical changes in the waste management in Vaasa region can be seen through the development of the one-bag throw-away culture into product-service systems of waste management. Recycling not only reduces dependency on landfills but also aligns with the EU's broader decarbonization and resource security goals. The European Commission highlights this by stating that *"the recycling of raw materials must be promoted and a strong secondary market enabled"* (European Commission, 2023).

Industrial symbiosis is another significant aspect of the circular economy in waste management whereby the firms can exchange resources and by-products in manners that replicate processes in the ecosystem. The Kalundborg Symbiosis, pioneered in Denmark, is frequently taken as the canonic example, where knowledge of the system has taken a pivotal role in industrial ecology, as participating companies have realized considerable environmental and economic returns over an incremental process over 40 years (Chertow & Ehrenfeld, 2012). Eco-industrial parks in Finland are designed to maximize the use of by-products and surplus resources. In Finland, 37% of industrial energy consumption is lost as heat, releasing more than 54 TWh into the environment annually, although about 4 TWh of this surplus heat can still be put to profitable use (Sitra, 2016). The forest industry also generates huge volumes of by-products that can be used to produce new products and increase the value added to forest resources. These side streams are already partly integrated into the circular economy and are closely linked to energy production, an area in which Finland is recognized as a pioneer at the international level (Sitra, 2016). These examples highlight how Finland applies a collaborative and regional approach to the circular economy, rooted firmly in its national CE roadmap.

With a more digitized world, the digital platform has become one of the crucial facilitators of the circular economy processes as they enable transparent and efficient matching of resources. The example of Finland is the Materiaalitori platform run by Motiva Oy, which is called Materiaalatori and is the process that will allow visualizing the material streams that are created in Finland and brought into one place and generate new possibilities to use the material and ensure that more materials are reused (Motiva, 2024). It is a digital market where companies, municipalities, and organizations can trade waste, by-products, and surplus materials, which should increase traceability and decrease the cost of transactions. These platforms combine data analytics to optimize matches, which opens the way to AI-driven improvements such as predictive matchmaking, which can predict supply-demand relations and reduce waste flows.

Waste-to-energy (WtE) is another mechanism that transforms non-recyclable waste into usable energy types such as electricity or heat. However, its role in the circular economy remains controversial, since it can conflict with higher levels of the waste hierarchy. As Korhonen et al., (2018) emphasize, waste-to-energy is often presented as part of the circular economy, but in practice it reduces incentives for recycling and reuse. They further caution that beyond WtE, the CE as a whole face's serious implementation challenges, particularly because recycling is constrained by thermodynamic limits that prevent complete material recovery (Korhonen et al., 2018). Finland uses Waste-to-energy as a residual recovery method of urban district heating recovery, usually of recycled residues. One area that studied the use of waste heat produced in an incineration plant in Vaasa was to determine its use in a residential area that was recently planned. The results revealed that the plant produced 45 GWh of excess heat in the summer season, which was enough to meet all the seasonal heating requirements, and the rest of the energy was stored in the seasonal energy storage facility of the district (Hirvonen & Kosonen, 2020). Nevertheless, the waste policy of Finland emphasizes that the recovery of energy must not be provided at the cost of recycling since the achievement of the recycling targets means that the level of mixed municipal waste referred to incineration must be decreased (EEA, 2025).

Importantly, these processes are also socio-technical ones where the technological innovations blend with social and institutional factors. According to Reike et al., (2018), the CE is a trendy yet rather disputable notion, which has received various definitions and interpretations. They also mention that the various schools of thought about the CE attach attention to various forms of value retention options (RVROs). As a matter of fact, effective CE in waste management is not only possible with tools such as sorting robotics, but stakeholder involvement, policy incentives, and cultural changes towards sustainability are also necessary. This is reflected in public education campaigns enhancing household compliance in sorting, accompanied by real-time feedback digital tools, in Finland. According to Peura et al., (2022) it is a longitudinal type of case study, which examines the creation of the pioneering waste management system in the Vaasa region of Western Finland. This kind of socio-technical integration is essential in scaling CE, especially with AI-infused digitalization, because it makes technology conform to human practices and organizational systems. Additionally, new processes such as extended producer responsibility (EPR) have an upstream extension of CE mechanisms that make manufacturers responsible in terms of end-of-life management. The mandates contained in the EPR directives of the Waste Framework require take-back systems of packaging and electronic materials, which stimulate recyclability in design (European Commission, 2020). Finland has an EPR that has resulted in innovations in waste collection, and companies such as Stormossen have partnered with producers to close loops efficiently.

2.1.4 Antecedents

The adoption and effectiveness of Circular Economy strategies and waste management depend on a set of initial factors that create a favorable environment for systemic change. This change requires the involvement of multiple social factors and their ability to collaborate to build positive change networks (Ghisellini, Cialani, & Ulgiati, 2016). From a human perspective, success depends not only on technology and organization but also on the interpersonal, organizational, and human relationships that support technological capabilities (Makarius et al., 2020). These antecedents encompassing regulatory frameworks, technological infrastructure, economic incentives, social acceptance, and institutional capacities interact dynamically to either facilitate or impede the implementation of CE principles (Kirchherr et al., 2017).

The Policy and Regulatory Frameworks serve as a background. It has some binding targets established by the European Waste Framework Directive (2008/98/EC) which include: by

2020, the member states must reach at least 50% of household waste recycling and 70% construction/demolition waste recycling and reinforced by 65% municipal waste recycling by 2035. (Article 11, European Parliament and Council, 2008; European Commission, 2020). It is an example of a regulatory push that makes Finland adjust its National Waste Plan 2023 to the EU goals because, according to the plan, Finland will recycle 55% of the municipal waste by 2025, 60% by 2030 and 65% by 2035 (Finnish Ministry of the Environment, 2023). Finland became the first nation to have a national CE roadmap as well (Sitra, 2016), now has a vision of global leadership in the circular transition. These policies offer both laws and financial and strategic guidance to the citizens and the businesses (Ellen MacArthur Foundation, 2015).

Infrastructure and Technological Capacity are a pivotal antecedent, providing the backbone for CE implementation. CE requires robust infrastructure to separate, collect, and process materials. In Finland, investments in advanced material recovery facilities, digital platforms (Materiaalitori), and district heating networks integrating waste-to-energy illustrate how technical capacity supports CE processes (Motiva, 2024; Hirvonen & Kosonen, 2020).

Stormossen is an example of such developments at the organizational level. The company states that more than 98% of all the waste that comes to the company is recycled or recovered (Stormossen, 2018). The waste management facility developed by Vaasa, as explained by Peura et al., (2022), has transformed into a complex product service system based on the initial model of a one-bag disposal system. This change, which is attained via the ever-growing development of infrastructure and social learning, proves the socio-technicality of the implementation of CE. The opportunities of AI integration also arise due to such developments, as well as predictive analytics and optimized waste collection.

Economic incentives continue to drive the adoption of sustainable energy use. Financial measures such as subsidies for industrial plants and tax incentives for companies participating in industrial symbiosis are part of Finland’s sustainable energy roadmap (Sitra, 2016). For example, while using 4 TWh of industrial heat per year demonstrates economic benefits, the high cost of digital platforms such as Materialitori poses barriers, especially for smaller communities (Sitra, 2016; Motiva, 2024). This requires targeted funding to address economic inequality. Promotion of a CE requires cultural and social values. Finland has a great environmental consciousness, and education has promoted great public involvement in recycling and reuse. On the policy level, the European Commission (2020, sec. 4.1) states that high-quality recycling depends on the successful separate collection of waste, which is why the central role of household behavior and involvement can be identified. Reliability of institutions and a sense of environmental responsibility are other elements that reinforce the acceptability of CE measures in society (EEA, 2020). The issue of a varied interpretation is still very problematic because the CE sphere is home to a variety of scholars who have different views on the field, and thus, it is difficult to reach a consensus on how to implement the concept.

Reike, Vermeulen, and Witjes (2018) attempt to solve this by offering a systemic framework of ten resource value retention options (ROs) to offer a better guideline of practice and policy. Regarding institutional capacity, it is critical to facilitate CE transitions, including in the governance system of Finland and organizations of partners to unite providers and users of recycled materials, such as Materiaalitori (Motiva, 2024). However, imbalanced regional capability is also a problem, and according to Tukker (2015), powerful legal and political reforms are required to scale such models as product-service systems. Successful CE also requires the involvement of people and cooperation of multi-actors, from EPR schemes to industrial symbiosis networks.

2.1.5 Effects (Environmental, Economic, and Social)

The implementation of CE principles of waste management has various environmental, economic, and social impacts that go beyond the classical waste minimization approaches. CE can help the societies overcome the ecological threshold, cost reduction, and community well-being, by changing the linear paradigm of take-make-dispose to regenerative systems (Ghisellini, Cialani, and Ulgiati, 2016).

In terms of environmental effects, one of the most direct impacts of CE practices in waste management is the reduction of environmental pressures through material recovery, recycling, and resource efficiency. CE reduces biodiversity, greenhouse gas (GHG) emissions, soil and water pollution, and decreases the use of landfills and incineration (European Environment Agency, 2022). The municipal waste recycling targets of the 65% by 2035 set by Finland are expected to help cut CO_2 by diverting the biodegradable waste of one company into the feedstock of another company, creating the following environmental impacts: less pollution and less dependence on importation of raw materials (Chertow & Ehrenfeld, 2012). CE offers significant ecological benefits in the Vaasa region, with less than 1% of material sent to the landfill by 2017, and approximately 60% recycled to produce energy and increase recycling efficiency by 45% as of 2012 (Peura et al., 2022). But the environmental benefits of a CE are limited by the laws of thermodynamics, as irreversible recycling processes consume energy, produce waste and often lead to the depletion of resources rather than their full recovery. (Korhonen et al., 2018).

The economic effects of CE are not limited to the direct reduction of waste, but also include an increase in resource security, cost-saving, and value-creating opportunities. Economic value is created through the activities of circular economy practices, where waste is converted into resource; reuse, repair and recycling activities are reducing dependence on virgin raw materials and hence increasing the resource security and reducing volatility in the global commodity market (European Commission, 2020)

Surplus industrial heat recovery, projected to be about 4 TWh/year in Finland, is an example of how CE strategies can be used to save money and offer alternative energy sources (Sitra, 2016). The trading of secondary materials between a company and organizations in digital marketplaces like Materiaalitori provide new opportunities to reuse and innovate business models and reduce transaction costs (Motiva, 2024). Also, research reveals that the application of AI to waste logistics, like the optimization of routes, can reduce transport distance, increase the efficiency of the operation, and the cost can reduce by up to 13% (Fang et al., 2023). On a macro level, the EU estimates that a shift to a CE could lead to cost savings of some 600 billion euros a year by 2030, especially in such major areas of the economy as waste management, construction, and manufacturing (European Commission, 2020). Social impacts of the practices of the circular economy are not limited to the material recovery and economic benefits; they can impact the employment patterns, the involvement of the population, the cultural norms, and the social justice outcomes. According to the European Environment Agency (2022), as of 2021, employment in the sphere of CE was over 4.3 million people, which is 10% more than in 2015, and activities like repairing, recycling, and reusing helped the sphere to grow.

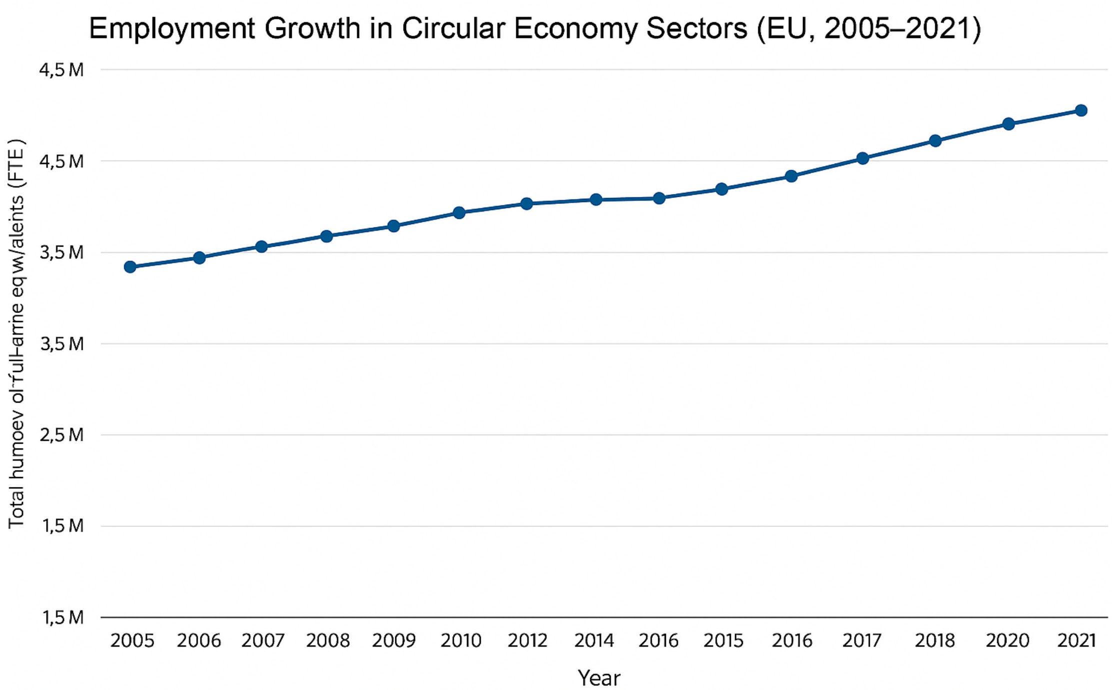

Figure 3 Employment Growth in CE Sectors

Adapted from the European Environment Agency (2008–2021)

Figure 3 shows the steady increase in employment within CE sectors across the European Union, reaching over 4.3 million jobs in 2021, a 10% rise since 2015. Employment includes activities such as recycling, repair, and reuse. Adapted from European Environment Agency (2022), "*CE in Europe: Key Indicators and Progress Report."*

In Finland and across Europe, citizen engagement and household behaviour play a central role in achieving high-quality recycling outcomes. As the European Commission's joint Research Centre notes, *'citizens'* behavior plays a key role in separate collection' (European Commission JRC, 2022). Similarly, Zero Waste Europe emphasizes that *'high quality recycling was reliant upon effective separate collection of waste'*, highlighting the need for strong public participation and well-structured collection systems (Zero Waste Europe, 2023). In Vaasa, the transition from a one-bag throw-away system to a source separation system requires a long-term social planning process, requiring significant changes in cultural attitudes, social norms, and organizational structures to establish effective networks between the city, industry, and citizens (Peura et al., 2022). Furthermore, Sustainable Development is also consistent with the goal of social equity, as waste reduction and recycling reduce environmental health risks that affect vulnerable and low-income groups in many countries (Siddiqua et al., 2022).

However, critics point to the dangers of "*greenwashing*" when the CE narrative is reduced to a technological solution, as this can lead to *"defining the issue in (and against) the inefficiency of capitalism"* and conveying "*the alluring promise of perfection, completeness, and infinity"* through circular explanations; the simplicity of this metaphor is misleading (Valenzuela and Böhm, 2017; Corvellec et al., 2021). The CE is an endeavor that generates environmental, economic and social advantages by mitigating pollution, enhancing efficiency and raising the level of participation and employment. Finland is an embodiment of this success with good recycling systems and a favorable culture. Nonetheless, the usefulness of CE lies in consideration of ecological constraints, economic hazards, as well as socio-political issues- demonstrating that CE is not a mere technical transition, but a wider socio-technical change demanding cultural and institutional reforms.

2.2 Stream 2: Digitalization and AI in Waste management

2.2.1 Broadly about the topic (history, background)

The emergence of Industry 4.0 represents a new industrial revolution, driven by the integration of Internet of Things (IoT) and related services into manufacturing environments, marking a significant shift toward intelligent and interconnected production systems (Kagermann, Wahlster, & Helbig, 2013). Although initially developed within the manufacturing sector, the concept of Industry 4.0 has progressively expanded to other industries, driven by its technological versatility and its potential to improve efficiency, flexibility, and sustainability across diverse contexts (Lasi, Fettke , & Kemper, 2014). Industry 4.0 builds upon previous industrial revolutions by integrating digital technologies such as the Internet of Things, data analytics, and AI into manufacturing systems, enabling interconnected and autonomous production that can dynamically respond to real-time information (Müller, Kiel , & Voigt, 2018), Within the waste management sector, digital transformation plays a critical role in supporting the transition from linear disposal models to circular resource flows.

According to the European Commission, technologies such as IoT, big data, blockchain, and AI can speed up circularity, support dematerialization, and reduce Europe's reliance on primary raw materials (European Commission, 2020). For example, digital technologies such as Internet of Things (IoT) applications are *'keeping track of valuable products and materials much more cheaply than in the past, radically increasing opportunities to recover them,'* while waste management technologies are also *'progressing quickly'* (Ellen MacArthur Foundation, 2015). IoT sensors and GPS technologies enable real-time tracking of waste generation and collection, while robotic systems support the automation of sorting processes in material recovery facilities, enhancing operational efficiency and recovery outcomes. According to the European Commission (2020), Digital technologies enable the monitoring and tracing of products, components, and materials throughout their life cycles, while ensuring that the associated data is stored and shared securely. supported by a

"European data space for smart circular applications" designed to facilitate product passports, resource mapping, and improved information flows within the CE framework (European Commission, 2020, Sec. 6.3).

These developments reflect a broader shift from manual, fragmented systems towards "*more integrated, data-driven systems"* in waste management (European Environment Agency, 2020). Digitalization is a structural enabler that connects the technological innovation with the goals of the CE and improves the efficiency, traceability, and sustainability. According to Müller, Kiel, and Voigt (2018), the digitization and integration of industrial processes with the help of data analytics, machine learning, and AI open new opportunities, in all aspects of sustainability. These technologies are not currently very widespread in the Finnish waste sector, but international experience indicates that they can contribute to the efficiency of operations and the development of agricultural economy principles.

2.2.2 Key Concepts and Definitions

Digitalization has become a key driver of organizational change in the Industry 4.0 era and represents a fundamental shift beyond the simple digitalization of existing processes or service products (Parviainen, Tihinen, Kääriäinen, & Teppola , 2017). Digitalization provides the opportunity to achieve the rapid growth of circularity through the introduction of innovative models based on technologies like IoT, big data, blockchain, and AI, and prompts a systemic shift in the production and service systems. (European Commission, 2020).

Unlike digitization, which involves converting analogue information into digital form, digitalization represents a more fundamental transformation that goes beyond simply digitizing existing processes or work products. (Parviainen, Tihinen, Kääriäinen, & Teppola , 2017). In the waste management sector, digitalization plays a key role by facilitating the identification of products, resources and materials, and by ensuring that data can be accessed and stored through the European data space, supporting better transparency and the circulation of circular resources. (European Commission, 2020). Building on these digital capabilities, automation plays a key role in translating digital information into efficient, reliable, and largely self-regulating operational processes. Automation means using control systems, software, and machines to ensure that work is done with minimal human intervention (IEA, 2017).

Automation has become a fundamental element of the current industrial revolution, increasing productivity, improving quality and reliability, and enabling the automation of routine operations through advanced sensors, sophisticated algorithms, and user-friendly interfaces (Frey & Osborne, 2017). through automation, in waste management, sorting material recycling facilities have been highly instrumental with robots sorting the recyclable materials using conveyor technologies which have been essential in ensuring that the facility can sort the material recycling load with high speed and accuracy, thus minimizing contamination and operation cost (Mesta, 2024). The IoT is a network of distinctly addressable physical objects equipped with sensors, RFID tags, and communication technologies, which interrelates and interacts using the Internet to complete common goals. (Atzori, Morabito, & Iera, 2010). waste management is adopting the use of IoT applications to support sensor-supported containers, GPS-driven collection trucks, and real-time tracking systems to enhance logistics and efficiency in collection (EIONET, 2020; Weghmann, 2013). Municipalities and private companies can use such technologies to optimize route collections, minimize fuel use, and enhance the dependability of services (European Commission, 2020).

The general definition of robotics is said to be the investigation of intelligent connection between sensing to actuation, including the design and the operation of systems that can accomplish autonomous/semi-autonomous tasks (Siciliano & Khatib , 2016). They consist of programmable machines and intelligent robots capable of executing physical complex assignments in predetermined working parameters (Siciliano & Khatib , 2016). within the waste management industry, more companies are launching robotic sorting apparatuses with sensors, cameras, and AI algorithms to recognize and separate various waste contents in waste streams and automate the sorting procedures and increase the capabilities of the system (Bogue, 2018; Kalirajan, Ramesh, & Vidyapeetham, 2025). Artificial Intelligence (AI) is interested in creating intelligent systems that can perceive the environment and respond to it. It is one branch of computer science that allows machines to think and make decisions like humans (Russell and Norvig, 2020; Copeland, 2021). In digitalization, AI can be used to optimize industry, increase its efficiency, and make decisions in real time by applying predictive maintenance, collaborative robots and digital twins (European Commission, 2021). In the waste management field, AI optimizes the collection paths and generally minimizes the transportation distances and expenses as well as attains sorting precisions of up to 99.95% (Fang et al., 2023). Scalable, predictive and efficient processes of circular economy are therefore made possible through the integration of AI with IoT, robotics and automation.

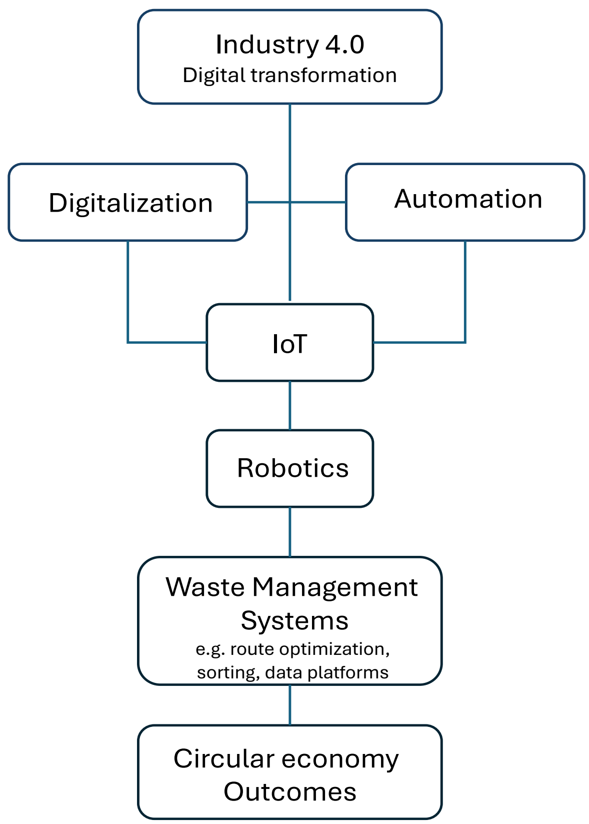

Figure 4 Overview of key digital technologies in waste management and their interconnections.

(Adapted from Morrar, R., Arman, H., & Mousa, S. (2017))

Figure 4 shows the interrelations between Industry 4.0 technologies and the outcomes of the circular economy in the framework of waste management. It shows how the IoT, robotics are enabled by digitalization and automation, which, in combination, can improve waste management systems that generate data to improve their sorting, route optimization, and material recovery. All these technological layers help facilitate the shift to the objectives of a circular economy including a greater efficiency of operations, an increase in recycling, and sustainable use of resources.

2.2.3 Processes and Mechanisms

Digital technologies such as the Internet of Things (IoT), big data, blockchain, and artificial intelligence (AI) are fundamental enablers of circular economy (CE) objectives. These technologies can be used to improve the efficient utilization of resources by enabling real-time monitoring of materials and developing digital resources like product passports and resource maps, which can speed up the material cycles and eliminate the use of virgin resources (European Commission, 2020; Ellen MacArthur Foundation, 2019).

As stated by Fang et al., (2023), real-time monitoring and AI-based planning are the major contributors to the efficiency and precision of waste collection and recycling as the main drivers of circular waste management systems. According to the European Environment Agency (2020) and Motiva (2025), all phases of the waste management process of collection, transportation, processing, recovery and recycling are now optimized with the help of digital technologies, which will facilitate the transition to the circular nature of the systems.

The first step is the data collection and sensing, during which smart bins, GPS monitors, and real-time information platforms with IoT power generate endless waves of incoming data on the volume of waste and the collection requirements. Data processing and analytics then use these digital inputs to predictive-based waste generation forecasts, anomalies, and assist in maintenance planning (Fang et al., 2023).

Based on this analytical base, optimization of operations is done by planning routes, robotic sorting and material recovery facility (MRFs) automation. They are deployed in systems that collect materials with the help of AI and machine vision, sorting them as accurately as possible, and reducing contamination and operational expenses (Bogue, 2019; Siciliano & Khatib, 2016). Such predictive models as the BIN-CT system show how effective waste-density forecasting can minimize unwarranted trips, fuel use, and negative impact on the environment (Ferrer & Alba, 2019).

The functioning of AI integration is based on a cross-cutting enabler that helps in all the waste management chain. It allows real-time decision-making, predictive maintenance, and optimization of adaptive processes, optimizes the operations and CE outcomes (Fang et al., 2023; Taheri et al., 2022). These processes are further facilitated by digital tools like Materiaalitori in Finland, which help a company and community to exchange secondary materials and services to enhance industrial symbiosis and minimize the cost of transactions (Motiva, 2024; European Commission, 2020).

Altogether, the mechanisms would lead to the results of a circular economy, such as a decrease in emissions, higher recycling rates, and more efficient use of resources. The AI and data-driven waste systems can therefore ensure the waste is managed as a proactive, intelligent, and sustainable process instead of a reactive and manual process. Digitization of waste management is hence one of the pillars of the circular economy, especially in highly developed settings like Finland, where innovation and data-oriented practices are gaining momentum in driving a paradigm shift in the system.

2.2.4 Antecedents: Enablers of Digital Transformation

Waste management requires several enablers to achieve digital transformation, with them being data quality, infrastructure preparedness, organizational capacities, and favorable institutional and cultural climate. According to Antikainen, Uusitalo and Kivikytö Reponen (2018), digitalization can improve the CE by offering relevant data on the availability, location, and condition of the products to help reduce wastes and increase the product life cycles. Nevertheless, they also mention that there are still significant difficulties in data management, cooperation, and development of competence which are still the key conditions of successful digital transformation.

Reliable and interoperable data systems are fundamental to this process, enabling accurate tracking of material flows and informed decision-making (Antikainen et al., 2018; Bindeeba et al., 2025). Rihm et al. (2024) emphasize that fragmented systems create “data silos” that hinder coordination among municipalities and recyclers, reinforcing the need for standardized data governance and integrated infrastructures. Finland’s Digital Decade Policy Programme 2030 promotes interoperability and cross-sector collaboration (Ministry of Finance Finland, 2024), yet local operators such as Stormossen still face challenges connecting legacy systems, highlighting the need for shared standards such as APIs and EU Waste Data Standards (European Commission, 2023).

The level of digital transformation is also depended on infrastructure and IoT preparedness. Although digital technologies, such as sensors and telematics yield useful real-time information (Rihm et al., 2024), their implementation is limited to poor connectivity, expensive nature, and maintenance requirements (Atofarati et al., 2025). Onur et al., (2024) and Neri et al., (2024) also emphasize that with the interoperable systems, the IoT, AI, and robotics may be used to significantly optimize the work processes. Finland is the global leader in broadband and 5G coverage, but rural coverage remains low, and this is why continuous network investment is necessary to serve operators in the region, such as Stormossen (Ministry of Finance Finland, 2024).

Another important antecedent is that of organizational readiness. The companies need to consider the use of digital tools as a part of their everyday routine and create an innovation-friendly, collaborative, and learning culture. As demonstrated by Bindeeba, Tukamushaba and Bakashaba (2025), digital transformation reinforces sustainable performance by enhancing productivity, environmental sustainability, as well as engagement with stakeholders. Ranta, Aarikka-Stenroos and Väisasnen (2021) focus on the importance of cultural preparedness and co-creation, whereas Corvellec, Stowell and Johansson (2021) stress the fact that institutional inertia may hinder development. The culture of transparency and high levels of trust in the population in Finland (Sitra, 2016) and its collaborative spaces, like the Materiaalitori portal (Motiva, 2024), offer positive external factors to participatory and transparent digitalization. at the policy level, the EU's CE Action Plan and Finland's CE Programme 2035 promote digital innovation, product traceability, and public–private cooperation (European Commission, 2020; Technology Industries of Finland, 2021). Although high costs and regulatory fragmentation persist (Rihm et al., 2024), these frameworks together with access to national and EU funding form a strong foundation for advancing AI-enabled circular waste management in Finland.

2.2.5 Effects and Outcomes

Digitalization and AI are transforming Finland's waste management sector by improving operational efficiency, environmental sustainability, and social participation, all of which support CE objectives. Antikainen, Uusitalo and Kivikytö-Reponen (2018) argue that digitalization enhances CE by enabling accurate tracking of product lifecycles, reducing waste generation, and improving material recovery. In the Finnish context, digital tools contribute directly to national CE targets by promoting data-driven decision-making, resource optimization, and transparency across waste systems (Ministry of the Environment Finland, 2021).

The effects of digitalization on waste management in the Finnish waste management sector are operational and environmental effects, which are becoming more visible. The use of digital technologies, including IoT sensors, telematics, or smart bins, is gradually improving the performance of waste collection, as well as mitigating emissions in Finnish municipalities. Materiaalitori is a platform that facilitates material reuse: it connects waste producers and users by means of digital interactions (Motiva, 2024). According to Rihm et al., (2024), digitalization enhances transparency and decision-making in the waste management system and promotes the transition to circularity. Likewise, Atofarati, Adogbeji and Enweremadu (2025), note that combining AI, IoT, and data analytics leads to the optimization of the operational processes as it allows monitoring operations in real-time and eliminates logistical waste. Finland's CE Programme also recognizes that digital data systems underpin the development of new business models and circular material flows (Technology Industries of Finland, 2021). In Vaasa, Stormossen's adoption of digital monitoring systems demonstrates how such integration can optimize waste transport and reporting while contributing to regional sustainability goals.

The economic effects and productivity gains of digital transformation in Finland's waste management sector are becoming increasingly evident. Digitalization enhances cost efficiency, operational control, and long-term resource productivity. According to Bindeeba, Tukamushaba and Bakashaba (2025), digitalization enhances sustainable business performance by reducing environmental impact and improving productivity through better process control. In Finland, regional waste operators supported by Business Finland and EU innovation funding have begun integrating data platforms to streamline operations and lower lifecycle costs. Atofarati, Adogbeji and Enweremadu (2025) also observe that smart waste systems generate long-term economic returns through reduced landfill dependency and energy savings an outcome increasingly evident in municipalities piloting AI-based data analytics for recycling optimization.

The waste management industry in Finland has not only been digitalized but also enhanced collaboration and cultural transformation in addition to increasing efficiency. According to Ranta, Aarikka-Stenroos and Väisänen (2021), digital technologies promote innovation through knowledge sharing and co-creation among various parties. On the same note, Sitra (2016) points out that the shift of the Finnish sustainability system to circularity is founded on openness and extensive stakeholder engagement, which are characteristic of the culture of trust and cooperation. Such circumstances allow municipalities, citizens, and organizations like Stormossen to create digital waste solutions together and empower employees, interdepartmental collaboration, and flexibility in their daily business. Although Finland's digital infrastructure is strong, regions like Ostrobothnia still face network limitations that hinder advanced AI adoption. Yet, opportunities in predictive analytics, smart grids, and robotics can boost resource recovery and support development. Strengthening cooperation, education, and information exchange will help players like

Stormossen use AI effectively for the circular economy. Overall, Finland’s experience shows that quality data, institutional readiness, and collaboration drive digitalization’s benefits and lay the groundwork for an AI-based circular economy.

2.3 Stream 3: Socio-Technical Systems (STS) Framework

2.3.1 Origins and Principles of STS

The Socio-Technical Systems (STS) framework originated in the 1950s through the foundational work of Emery and Trist at the Tavistock Institute in London. They also came up with the concept of socio-technical systems to refer to the systems which engage a complex interplay of man, machines and the environment (Baxter and Sommerville, 2011). This viewpoint focuses on the fact that every organizational work system comprises of interdependent technical and social subsystems that need to be optimized collectively to ensure that maximum overall performance is achieved (Ogie et al., 2022), Molleman and Broekhuis, 2001). Over time, STS has become one of the essential theoretical tools of organizational design and digital transformation, as it has acknowledged that digitalization can only achieve success when technological systems are brought to correspond with both social and organizational processes (Zhang et al., 2023). Some of the latest research indicate that a socio-technical approach may be used to understand the process of interaction between skills and digital resources during the stages of change and obtain synergistic results (Iden & Bygstad, 2025).

In Finland’s waste-management sector, this dual perspective is especially relevant, as innovations such as AI-driven logistics, IoT monitoring, and data analytics depend on workforce adaptability, inter-organizational collaboration, and a culture of continuous learning. The framework is typically represented as two interconnected subsystems the social and the technical operating within an external environment that influences their interaction (Molleman & Broekhuis, 2001). When these elements are balanced, socio-technical design “recognizes that organizational performance depends on balancing technology with the needs of people” (Mumford, 2006). This interaction can be visualized through the Socio-Technical Systems (STS) framework, which highlights how social and technical subsystems jointly operate within an environmental context to achieve organizational and circular economy outcomes (Figure 5).

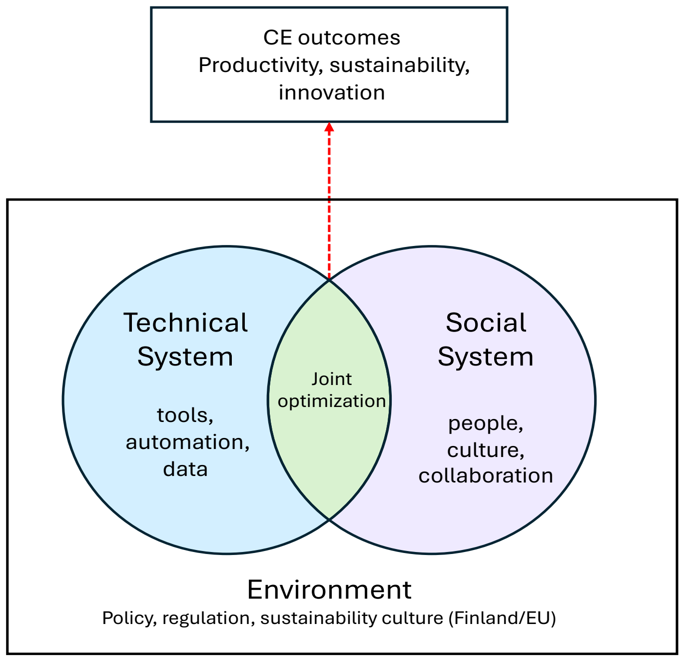

Figure 5: Socio-Technical Systems Framework

(Adapted from Baxter, G., & Sommerville, I. (2011))

As shown in Figure 5, this framework illustrates how technological tools and social processes jointly drive digital transformation and circular economy (CE) outcomes. The technical subsystem comprising Digital tools, automation, and data enables data-driven operations and the efficient flow of resources. The social subsystem, which includes leadership, workforce competence, stakeholder engagement, and organizational culture, supports the adoption, integration, and sustained use of these technologies. Surrounding both is the environmental layer, representing external factors such as policy frameworks, regulatory conditions, and economic influences that shape how digital transformation practices unfold. This conceptualization is adapted from Baxter and Sommerville (2011) and Molleman and Broekhuis (2001).

2.3.2 Applications in Organizations and Digitalization

The Socio-Technical Systems (STS) approach is a valuable lens through which one can analyze the process of digital integration in organizations and social resiliency and change. In an organizational context, Socio-Technical Systems emphasizes that digital transformation is not just a technological upgrade but a holistic transformation that includes processes, people, and culture. (Baxter & Sommerville, 2011). Effective digitalization requires the optimal integration of technological systems such as information systems, automation, and data analysis, as well as social systems such as human skills, leadership, and collaboration practices (Molleman and Broekhuis, 2001).

In the Finnish waste management sector, the application of Socio-Technical Systems principles is clear in how organizations approach digital transformation to achieve their circular economy goals. To demonstrate the duality of the Socio-Technical Systems model, a case of municipal operators, Stormossen, in Vaasa, can be given as an example: the technical subsystem is composed of the IoT sensors, vehicle telematics, and data-driven collection systems, whereas the social subsystem is comprised of workforce training, collaborative governance, and involvement of the population. The alignment improves organizational learning, effectiveness and trust major results of successful socio-technical integration (Iden and Bygstad, 2025).

The socio-technical interaction in Finland's waste sector illustrates the relationship between technology and people, enabling the realization of circular economy outcomes. Socio-Technical Systems theory also highlights the interdependence between technological tools and human agency during digital transitions. Zhang et al. (2023) argue that a socio-technical perspective helps bridge data systems with organizational processes, reducing information asymmetry and promoting sustainable “green transformation.” This is reflected in practice by the Materiaalitori platform in Finland, which connects waste producers and users through digital interactions and requires both credible digital infrastructure and stakeholder involvement (Motiva, 2024).

Policy frameworks serve as external frameworks that shape social cohesion. Finland's CE Programme 2035 emphasizes the importance of data and technology tools for monitoring and ensuring circularity, while the EU Digital Decade Policy Programme calls for broad collaboration between the public, private and third sectors to promote digital and data-driven economies (Industries Technology Finland, 2021; Ministry of Finance Finland, 2024). Together, these policies support organizations to integrate digital processes into inclusive, people-centered processes. As Mumford (2006) argues, achieving a balance between technology and people is essential to achieving both operational efficiency and employee well-being. Finally, the analysis of the waste management digitalization in Finland according to the framework of Socio-Technical Systems proves that the technological investments are not enough without the supportive organizational structures and collaborative cultures. Joint optimization -human competence, digital tools, institutional alignment form the basis of adaptive, sustainable, and participatory digital transformation.

2.3.3 AI Integration and Socio-Technical Capital

While the implementation of Artificial Intelligence (AI) into the waste-management industry in Finland is in its new stage, it is the next digital revolution and the major facilitator of the transition to the circular economy. In the context of Socio-Technical Systems (STS), AI is a digital mediator that enhances the relations between the technological and social subsystems. The technical subsystem is made of technologies, processes, and digital tools, which transform inputs into outputs, and the social subsystem is made of people, skills, collaboration, and organizational culture that maintain these processes (Ogie et al., 2022). The effectiveness of an organization is the significance of harmonious synergy of the two subsystems, not a single system over the other (Baxter & Sommerville, 2011). Therefore, to achieve effective AI incorporation, it is essential to align automation, data analytics and monitoring tools and systems with human capabilities, collaboration and flexibility to ensure sustainable and inclusive change (Molleman & Broekhuis, 2001).

AI functions both at the boundary between technologies and social systems, which enhances their interdependence in a wider environmental agenda determined by national policy, regulatory frameworks, and the objectives of the circular economy. This combination shows that AI is not only a technological change but also a social change mechanism that redefines organizational practices, education and governance systems. According to Iden and Bygstad (2025), the application of a socio-technical lens explains interactions between digital skills and resources at different levels of transformation to generate organizational impacts. On the same note, Zhang et al., (2023) point out that digital transformation facilitates green innovation by harmonizing data systems and institutional processes and closing knowledge gaps. Successful adoption of AI relies on factors such as cultural readiness, digital literacy, and institutional trust. This trust is a key component of what scholars refer to as social capital, the interconnected networks of people, technologies, and relationships that enable innovation (Sarker, Chatterjee, & Xiao, 2013). In Finland, national plans such as the Digital Compass 2030 and the Circular Economy Programme 2035 emphasize data collaboration and technological innovation as key elements for sustainable development (Ministry of Finance of Finland, 2024; Technology Industries of Finland, 2021). The Digital Compass aligns Finland's digital vision with the EU's Digital Decade, while the Circular Economy Programme emphasizes the importance of data systems to track trends and promote resource circularity.

Through a combination of these frameworks, regional players like Stormossen can integrate AI in sorting waste, optimization of routes, and material analytics. Though the procedures of Stormossen are still based mainly on the IoT-based surveillance, the high rate of teamwork and the presence of skilled employees offer an opportunity to make the gradual transition to the use of AI, aided by the collaboration with the University of Vaasa, VEBIC, and technology vendors. Such human-technology synergy covers the focus of Finland on ethical and participatory AI application, which is based on trust, transparency, and openness (Sitra, 2016).

Finally, the use of AI in waste management reflects the principle of the STS according to which technological efficiency and social well-being are to move in the same direction. Applied to the participatory and collaborative systems, AI increases predictability, quality of services, and organizational learning (Atofarati et al., 2025). Thus, the sustainable change in waste management depends not only on the innovativeness of technologies but also on human capability, collaboration, and learning to adapt to each other to make the socio-technical capital that leads to the transformation of the Finnish circular economy.

2.3.4 Relevance for CE and Waste Management

This section will build on the socio-technical and AI integration framework and explain the role of these dynamics in promoting the implementation of the CE in the waste-management industry. The CE strives to reduce waste, maximize resource use through reuse, recycling, as well as sustainable production structures. In this context, digitalization and AI are facilitating powers that rationalize data-driven decision-making, optimize operations, and reinforce the partnership among stakeholders in the waste value chains (Ellen MacArthur Foundation, 2023). The Socio-Technical Systems (STS) framework is the framework that helps in the interpretation of how the union of human and technological abilities can facilitate the circular transition and ensure that the technological improvements are incorporated into organizational and social structures.

The Socio-Technical Systems view of waste management emphasizes the fact that digital devices and AI can only reach their potential in the context of collaborative governance, adaptive cultures, and skilled labor. The linking of technical and social subsystems facilitates sustainable innovation in accordance with the aims of the. To provide an example, waste generation, route optimization, and more efficient sorting can be predicted with the help of AI-powered data analytics, whereas social aspects (employee skills, leadership, and citizen engagement) guarantee their responsible implementation (Zhang et al., 2023). Thus, AI is a technical and relationship facilitator, which unites people, information, and processes to obtain resource-efficient outcomes. In Finland, the CE programme 2035 focuses on leveraging data and digital tools to track material and energy flows, but the Digital Compass 2030 promotes the adoption of ethical AI and open data to promote cross-sector cooperation (Ministry of Finance Finland, 2024; Technology Industries of Finland, 2021). These frameworks in combination can help local actors like Stormossen in Vaasa, where monitoring IoT, inter-municipal collaboration, and collaboration with VEBIC and the University of Vaasa can demonstrate that digital innovation combined with social collaboration can lead to quantifiable positive environmental outcomes.

In addition, the integration of AI can facilitate CE principles, such as the development of feedback mechanisms that can be used to engage in an unceasing learning process and optimize performance. As an illustration, predictive analytics might be used to detect areas of inefficiency in recycling streams, and automated data-sharing systems enhance municipalities, company, and citizen coordination (Atofarati et al., 2025). These systems create transparency and accountability required to attain long term sustainability objectives.

Nevertheless, until the technical capacity, as the Socio-Technical Systems framework reminds us, the success of these technologies is highly reliant on the human trust, competence, and organizational adaptability (Baxter and Sommerville, 2011; Sarker et al., 2021). Finally, AI and socio-technical integration are relevant to CE, as they can both contribute to intelligent, participatory, and adaptive systems of waste management. Considering AI as a part of socio-technical capital, organizations will be able to stop following efficiency and start to pursue human, ethical, and sustainable digital transformation. Through this, the waste-management industry in Finland is a bright example of how technological and social innovation can speed up the process of changing the future to the circular, low-carbon one.

2.4 Proposed Conceptual Framework

In this section, the conceptual framework that combines the principles of Artificial Intelligence (AI), Socio-Technical Systems (STS), and Circular Economy (CE) is presented to explain how digitalization can help the waste management industry in Finland to become more sustainable in the context of sustainable innovation. The framework is based on the Socio-Technical Systems theory, which assumes that the optimization of social and technical subsystems, instead of handling them separately, provides an organization with effective performance (Trist 1951, Baxter 2011). In this study, AI is seen not as an easy-to-use technological device but as an enabler, which empowers the connection between individuals, technologies, and institutions to deliver CE-oriented results.

Using the STS perspective, this framework recognizes that digital transformation can only be successful with technological development being in line with social preparedness, organizational culture and policy environments. Examples of such alignment in the waste management industry of Finland include the implementation of IoT-based surveillance and route optimization, as well as data-sharing systems by Stormossen, which encourage environmental effectiveness and stakeholder cooperation. With the suggested framework (Figure 8), AI is, therefore, a linking factor bridging the technical and social subsystems with enabling environmental and policy conditions, leading to sustainable and circular results.

2.4.1 Contextual Foundation

Contextual foundation gives the facilitating environment under which socio-technical interactions take place. In Finland, high policy orientation, technological development and engagement of people towards sustainability are the features of this context. At the national level, institutional support of waste reduction, resource circulation and innovation is offered by such frameworks as the Circular Economy Roadmap (Sitra, 2016), the EU Waste Framework Directive, and the Waste Act of Finland (Ministry of the Environment Finland, 2023). In line with these environmental policies, the Digital Compass 2030 strategy (Ministry of Finance Finland, 2024) focuses on the adoption of data, automation, and AI to enhance the level of innovation in the public and private sectors towards the idea of sustainability.
Stormossen in the Vaasa region is at the organizational level and represents a practical example of this policy environment in action. The firm works under the well-established

values of collaborative, transparency, and employee engagement, which support the socio-technical philosophy of the integration of the human and technical subsystems (Peura et al., 2022). Stormossen illustrates that AI-based tools can be useful in reaching efficiency and environmental objectives through digital route planning, biowaste monitoring, and data analytics. Therefore, these contextual factors policy frameworks, organizational culture, and circular economy orientation comprise the layer one of the conceptual frameworks. They influence the way digital technologies such as AI could be successfully implemented in the waste management system of Finland and turned into the results of sustainability and a circle.

2.4.2 Social-Technical Interaction

The fundamental part of the framework is the AI-based socio-technical interaction, which is the dynamic interaction between the technical and social subsystems of an organization. Technologies that make up the technical subsystem can be categorized as AI algorithms, IoT sensors, automation tools, and data analytics platforms that are used to optimize operations, improve decision-making, and enhance traceability (Fang et al., 2023).These tools make it possible to predictively collect waste, automate sorting and real-time tracking which has helped in efficiency and transparency in waste management. By contrast, the social subsystem encompasses the following aspects leadership commitment, employee skills, collaboration between the stakeholders, and the organizational culture (Baxter and Sommerville, 2011; Molleman and Broekhuis, 2001). These are determinants of the effectiveness of the adoption, trust and maintenance of technology. As an example, leaders' vision and workforce training are critical in making sure that integrating AI is not only ethical but effective as well.

AI functions as a bridge between these subsystems, acting as a digital mediator that transforms technological potential into socially meaningful outcomes (Iden & Bygstad, 2025). When implemented through the STS lens, AI facilitates collaboration, enhances learning, and supports participatory governance, ensuring that technological innovation remains aligned with human values. This interaction is essential in the Finnish waste management setting as digital tools do not replace employees but make them more empowered, which leads them to develop a culture of trust, responsibility, and flexibility (Zhang et al., 2023). This form of the framework indicates the principle of joint optimality where the efficiency of the organization and the social well-being can enhance at the same time when the social and technical aspects are co-designed to be complementary to each other (Trist and Bamforth, 1951; Emery and Trist 1960).

2.4.3 Circular Economy Outcomes

The results of successful socio-technical integration of AI are reflected in the tangible gains in the performance of the circular economy. These deliverables are - Enhanced Resource Efficiency and Operational Effectiveness, predictive analytics and automation can increase, sorting waste, optimization of routes, and recycling efficiency (Wilts, 2021; Fang et al., 2023), and Waste Reduction and Material Recovery digital platforms enable material flows to be tracked in real-time, facilitate reuse, recycling, and recovery thus reducing dependence on landfill operations (Ellen MacArthur Foundation & McKinsey, 2019), and Collaborative Innovation and Sustain. These outcomes highlight how AI-driven digitalization contributes to CE transitions not only by improving efficiency but also by encouraging social inclusion, transparency, and systemic innovation. The interaction between technical and social elements fosters ongoing learning and feedback, leading to long-term improvements in sustainability performance.

2.4.4 Conceptual Lens: Linking AI, STS, and CE

Contextual foundations impact socio-technical interactions, and the impacts of these interactions on the results of the circular economy are represented as the conceptual framework (Figure 8). It demonstrates that AI exists at the crossroads of the technical and social subsystems and as the integrative mechanism that leads to the digital transformation without compromising human values.

This framework moves beyond linear cause-and-effect models by emphasizing relationships, processes, and adaptive change, key characteristics of qualitative inquiry. It is not designed to test hypotheses but to interpret how AI-driven digitalization fosters sustainability through social and technical co-evolution (Sarker et al., 2019; Iden & Bygstad, 2025).

Conceptually, the framework contributes to both theory and practice in several ways:

1. Applying the STS Perspective to Sustainability Transitions: It expands the classical theory of socio-technical systems to the transitions to AI in CE, demonstrating the ability of digital tools to support the goals of circular and sustainability in the realms of public and waste management (Baxter and Sommerville, 2011).
2. It is important to emphasize the Role of Organizational Readiness and Culture: The framework shows that the digital transformation requires the organizational readiness, leadership commitment, and a learning culture. In the absence of them, such technical tools as AI are incompletely used or not sustainable (Molleman & Broekhuis, 2001; Zhang et al., 2023).
3. Promoting a Human-Centered Approach to AI Integration: Instead of framing AI as a substitute for human work, the framework emphasizes its role in supporting decision-making, collaboration, and ethical governance ensuring that automation complements human judgment (Ellen MacArthur Foundation, 2023).
4. Bridging Policy and Practice: It connects Finland's national strategies, such as the Digital Compass 2030 and CE Roadmap, with the organizational realities of Stormossen, showing how multilevel governance enables local innovation and sustainability outcomes (Ministry of Finance Finland, 2024; Sitra, 2016).

Therefore, the framework is the analytical basis of the following empirical chapters. It informs data gathering, analysis, and interpretation by describing how socio-technical alignment that has been made possible by AI and digitalization can help reduce wastes, recover resources, and introduce sustainable innovation into the CE transition in Finland. Finally, this theoretical perspective demonstrates that achieving the success of AI-based digitalization is not just about technological progress but also in the implementation of social learning, ethics governance, and joint innovation principles, which are closely related to the idea of a human-centered circular economy in Finland.

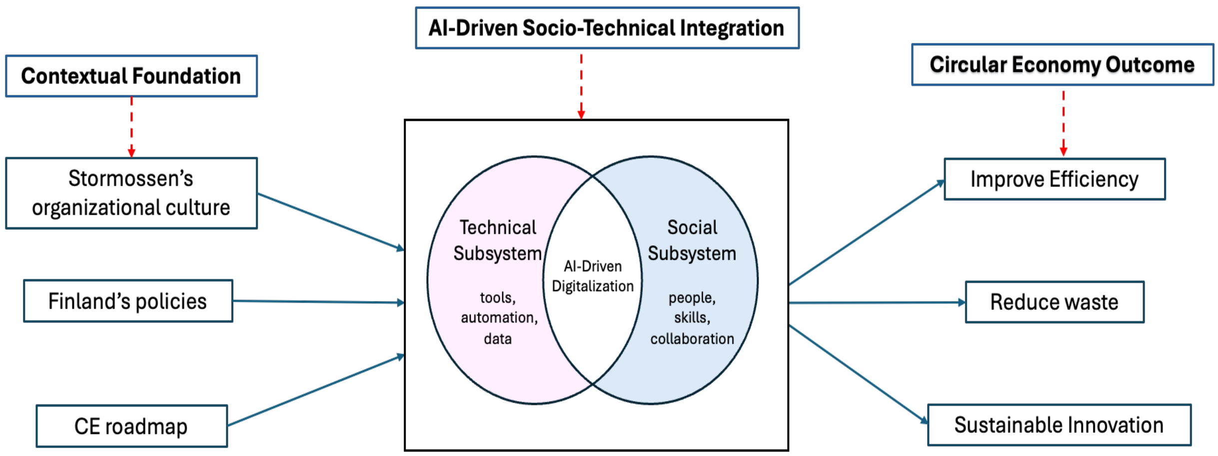

Figure 6: Conceptual Framework
(Source: Author's own illustration, 2025.)

As shown as in the figure 6 conceptual framework synthesizes theoretical insights from the Socio-Technical Systems (STS) perspective and the principles of the Circular Economy (CE), illustrating how AI functions as a mediating mechanism between human and technological systems. Organizing the social competency and conducive policy environments with technical infrastructures will enable organizations like Stormossen to accomplish greater recycling efficiencies, data-driven decision-making and sustainable innovation. Based on this, the structure serves as the analytical basis of the subsequent chapters, which are used in the data analysis (Chapter 3) and empirical evidence (Chapter 4). It is a gap bridging between theory and practice by putting in perspective how AI-enabled socio-technical integration can facilitate the shift of Finland towards a more sustainable and circular waste management system.

3. METHODOLOGY

3.1 Research Strategy and Method

The choice of the right methodology forms the basis of the quality and credibility of a research study (Edmondson and McManus, 2007). The design shall be congruent with the research goals, and the research question. This study explores how digitalization, including AI, contributes to CE practices in Finland's waste management sector, using Stormossen as a case study. Since the subject is social, technological, and organizational interactions, the qualitative method was deemed to be the most appropriate to address the complexity of the processes. Figure 7, which is built on the Research Onion by Saunders et al., (2019), a representation of the methodological framework of this study. The model presents the most critical methodological choices informing a research design between philosophical orientation and data collection and analysis methods. The onion layers are used to denote each phase of the research narrowing down the methodological focus, and this guarantees internal consistency throughout the research process.

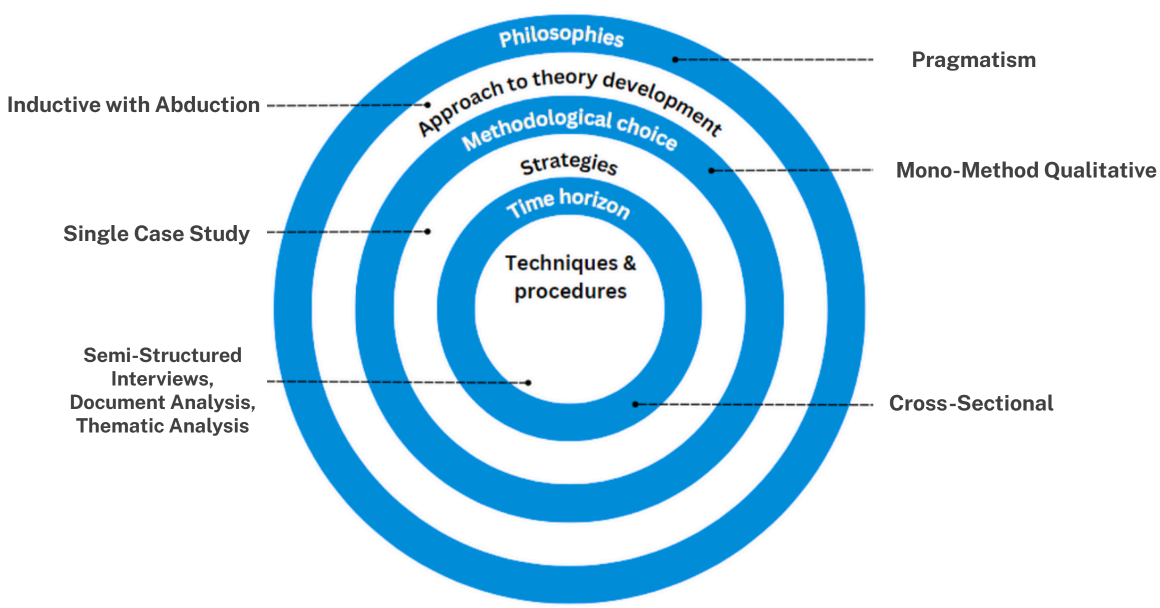

Figure 7 : Research Onion for the Study

(Adapted from Saunders et al., 2019)

The outer layer defines the philosophical position of the study. This study has a pragmatic research philosophy, which allows flexibility of the methodology and aims at discovering practical solutions to the problems of the real world. Pragmatism acknowledges that no one single viewpoint can bring into focus the complex social reality; rather, it incorporates both objective (e.g., the impact of measurable technology) and subjective (e.g., perceptions of the organization) insights as a way of responding to the research question in the most effective manner (Saunders et al., 2019). This philosophy begins with the research problem itself realizing the joint effect of technology and human factors on the practices of CE emphasizing the creation of actionable insights. This correlates well with the Socio-Technical Systems (STS) theory that recognizes technology and human systems as interdependent and focuses on the combined optimization of the two to achieve organizational success (Trist and Bamforth, 1951; Emery and Trist, 1960). The pluralistic ontology (various realities) and practical epistemology (knowledge based on what works) of pragmatism fit the central subject of the study on socio-technical interactions in waste management, which are relevant to a variety of stakeholders such as companies and policymakers.

The second layer determines ways in which theory is developed. The research is inductive research with some abduction elements. Inductive approach the approach constructs theory based on the empirical findings, where patterns, themes and meanings are extracted out of the data as opposed to the application of existing hypotheses (Saunders et al., 2019). It is appropriate to investigate a developing and little studied field such as AI-driven digitalization in CE practices, and the information is obtained through the context of the case study. Aspects of abduction are achieved by repetitive movement among the current theory (e.g., STS and CE literature) and the empirical results to achieve a better understanding. It is an abductive process that allows a subtle interpretation that is empirically based but theoretically informed, in keeping with the pragmatist focus on solving problems practically and flexibly.

The third layer defines the methodological design in general. The paper employs a mono-methodology qualitative methodology through which the researcher examines non-quantitative data to examine in detail the phenomenon of social, technological, and organizational processes. In complex socio-technical situations, especially the perception, attitudes, behaviors, and interactions that quantitative techniques fail to capture, qualitative methods are best used to show them (Saunders et al., 2019). The decision will allow establishing coherence and depth by relying on multiple qualitative sources (e.g., interviews and documents) and maintaining the focus. The triangulation of data sources increases the validity that can clarify the interpretively aspect of the research question as well as the pragmatic philosophy.

The fourth layer explains the plan for how the research shall be carried out. It is a single case study approach that is used to research complex real-world phenomena in their contextual boundaries (Yin, 2018). Such a method is especially useful with questions of the types of how, why, and it is possible to conduct an in-depth exploration of the role of digitalization in CE practices. The case in point is Stormossen, a local waste management organization in Vaasa, Finland. The case is a critical and revelation case because of its high recycling performance (98 -99%), excellent CE adoption, and early products to digitalization and AI programs. The single-case design can explore with great depth and analytical generalization (not statistical) and offers insight into socio-technical processes in waste management.

The fifth layer is concerned with the temporal scope. The paper will embrace a cross-sectional time horizon, indicating that the data will be obtained over a specified time frame (July to October 2025). The design is a detailed snapshot of the digitalization efforts, organizational processes, and CE practices in Stormossen at a certain moment in time as opposed to following change longitudinally. It is consistent with the qualitative, pragmatic emphasis in comprehending the present situation of change, with depth rather than temporal change.

The last step is the innermost layer that explains the practical approaches to data collection and analysis. The data will be collected through semi-structured interviews with four employees of primary functional departments at Stormossen (management and strategy, sorting and recycling operations, IT and data systems, and operations/logistics with frontline views). They are supplemented by the document analysis of company reports, the policies of waste management in Finland, and archival material. This multi-source method offers triangulated data, which increases the construct validity (Yin, 2018). The analysis of the data is based on the thematic analysis that follows the six-phase framework proposed by Braun and Clarke (2006): familiarization with the data, initial code generation, theme search, theme review, theme definition and naming, and report generation. This approach determines socio-technical dynamics of digitalization and CE consequences, which contribute to the inductive line of reasoning and theory building.

3.2 Case Selection

To achieve the relevance and depth of qualitative results, it is necessary to identify an appropriate case (Yin, 2018). The current research paper assumes a single-case study based on Stormossen Oy Ab, which is a local waste management company in the Vaasa area in Ostrobothnia, Finland. Stormossen is a local initiative regarding the application of the CE, recycling waste and digital transformation, which is a municipal alliance of six cities. This company was selected using the purposeful sampling technique, and the sampling approach is commonly used in qualitative case studies to find information-rich cases, which may assist in understanding the phenomenon in question in-depth (Patton, 2014).

Stormossen represents a critical and revelatory case for several reasons. First, it ranks among the top waste management centres in Finland, with a high recycling rate of between 98% and 99% (Peura et al., 2022; Stormossen, 2024). The project demonstrates its high level of implementation of progressive learning principles such as resource recovery, reuse, and waste reduction, and provides a case study for examining how digital tools contribute to progressive learning outcomes. Second, Stormossen has begun to implement initial digital and AI-related projects, such as waste tracking based on IoT, self-service vehicle terminals, and logistics optimization systems based on data. These efforts will provide the nice chance to understand the feasible interaction of technology and sustainability in a socio technical system.

The case also has theoretical implications since it is possible to conduct a comprehensive analysis of the interaction of digitalization as an emerging element with organizational and social processes to promote the CE aspirations. Yin (2018) asserts that single-case studies are most suitable in situations where the case is critical or unique or exemplary and that the case can generalize analytically to the rest of the theoretical constructs instead of statistical generalization. The operations of Stormossen, used in this paper, provide empirical illumination on the engagement of technical subsystems (digital platforms, IoT sensors, AI tools) and social subsystems (employee conduct, how decisions are made by the management, and organizational culture) as theorized by the Socio-Technical Systems (STS) theory. Access to the case was confirmed by the company management, who permitted interviews and document-based data collection. Data sources included company reports, local government policy documents, and the Finnish National CE Strategy, enabling a variety of perspectives to be triangulated. The combination of company data and contextual information is strengthened in this study and is consistent with Yin's (2018) principle of using multiple sources of evidence in case studies.

As such, Stormossen provides a systematic and rich case study for exploring the potential of AI-enabled digitalization in waste management focused on CE. Its broad scope, technological innovation, and enduring leadership make it a good fit to explore the research question: How does digitalization, including AI, contribute to CE practices in the Finnish waste management sector? The insights gained from this case study are expected to contribute to the development of ideas within the Socio-Technical Systems framework and to provide useful guidance for other organizations seeking to digitalize their CE processes.

3.3 Data Collection

Data collection for this study followed a multi-method qualitative approach combining well-structured interviews and document analysis to ensure methodological triangulation and increase efficiency (Yin, 2018). The methodology offers contextual and detailed insights into the role digital technologies, such as AI, play in terms of CE practices and waste management in terms of social and technological interactions.

3.3.1 Semi-Structured Interviews

Semi-structured interviews were selected as the main form of data collection because of the flexibility they offer when it comes to examining complex and contextual variables (Kallio et al., 2016). The interviews would comprise a set of open-ended questions that would help to retrieve the experiences, thoughts, and opinions of participants regarding the digital and AI-enabled Stormossen project.

Due to time constraints and limited access, only a small number of interviews were conducted. Therefore, document analysis was emphasized to complement and triangulate the findings. This approach ensured methodological rigor despite the limited primary data.

Four participants were interviewed, who are representatives of the four functional areas of Stormossen:

1. Management and Strategy - concerned with CE objectives, policies, and digital strategies.
2. Operations and Logistics / Frontline Staff - specialized in digital assistance applied in waste collection, transportation, and drivers (joint interview).
3. Sorting and Recycling Facility - is based on automation, sorting technology, and efficiency in processes.
4. Data and IT Systems - Data management, monitoring tools, and AI potential.

The interviews were 45-60 minutes and were conducted in English during the period between July and October 2025. All interviews were recorded and transcribed verbatim with the informed consent and transcribed verbatim into a later analysis. In line with the ethics of the University of Vaasa, the participants received anonymity to ensure confidentiality and transparency of the responses.

The interview guide (Appendix 1) was developed around key themes aligned with the research questions, focusing on the use of digital and AI tools in daily operations, organizational and workforce adaptation to technology, perceived benefits and challenges in achieving circular economy outcomes, and future opportunities for digital transformation. This approach enabled a comprehensive understanding of both technological aspects, such as digital systems, automation, and data utilization and human interactions, including skills, leadership, and collaboration, in accordance with the Socio-Technical Systems (STS) framework under which this study was conducted.

3.3.2 Document Analysis

To complement the interview data, a document analysis was conducted to contextualize and triangulate the findings. Evidence of Stormossen's digital and circular practices was gathered from organizational and policy documents, while macro-level insights on Finland's transition toward a circular economy were derived from external reports. The analysis incorporated materials such as Stormossen's annual and sustainability reports, the Finnish Ministry of the Environment's (2021) Circular Economy Programme 2035, Stormossen's official webpage and policy documents on digital initiatives and recycling performance, the study by Peura et al., (2022) on waste system development in the Vaasa region, and documentation from Motiva (2024) regarding the Materiaalitori digital platform. These sources were instrumental in tracing how institutional policies, digital infrastructures, and organizational actions align with circular economy objectives. The document analysis further strengthened data triangulation, ensuring reliability by cross-verifying interview insights with official records and published data.

3.4 Data Analysis

The data analysis stage was a crucial component of this qualitative study, providing a systematic process for interpreting raw data and generating meaningful insights within the theoretical context of the research. Thematic analysis was employed to identify, categorize, and interpret recurring patterns and relationships concerning technology use, organizational dynamics, and sustainability outcomes in Stormossen's circular economy (CE) practices. Thematic analysis (Braun & Clarke, 2006) was used to identify patterns related to digital tools, data practices, organizational dynamics, and CE outcomes in Stormossen.

The analysis was conducted according to the six phases of the analysis provided by Braun and Clarke (2006), and this included familiarization with the data, creation of the initial codes, creation and identification of themes, and finally the definition and interpretation of themes to create the final analytical narrative. The analysis combined inductive coding with deductive sensitization from the Socio-Technical Systems (STS) framework, ensuring that candidate themes were checked against both the data and relevant theory.

Step 1: Familiarization. Interview transcripts were transcribed and read repeatedly. Observation notes were reviewed for signals of digital readiness, AI experimentation, employee adaptation, and CE outcomes. Public documents (e.g., Stormossen reports, Finnish waste management and CE policies, and EU guidelines) were scanned to add contextual depth and triangulate insights (Yin, 2018).

Step 2: As this study was conducted without qualitative analysis software, manual line-by-line coding was performed on all interview transcripts and documents. Codes captured references to technological tools, data practices, organizational behaviors, and environmental impacts. The coding process was iteratively refined using both inductive insights from the data and deductive prompts informed by the Socio-Technical Systems (STS) framework.

Steps 3-4: Related codes were clustered into potential themes that captured broader patterns across data sources. Overlaps and inconsistencies were reconciled through repeated comparison of interview, document, and observational data. Each candidate theme was reviewed for internal coherence and clear distinction from other themes. The emerging thematic structure was further refined and validated against relevant literature to ensure both empirical robustness and theoretical relevance (e.g., Peura et al., 2022; Fang et al., 2023).

Step 5: The research identified eight main themes that capture the distinct yet interconnected aspects of AI-assisted digitalization and its relationship to circular economy performance: Contextual Foundation, Digital Integration and Tools, Data Collection and Usage, Organizational Adaptation and Learning, Socio-Technical Interactions and Joint Optimization, CE Outcomes, Challenges and Opportunities, and Emerging Directions and AI Potential. Final definitions and labels for these themes were refined through iterative discussion and recorded in a codebook to guide the reporting of results.

The last stage of analysis was the arrangement of the eight themes into the coherent flow of reasoning linking the empirical evidence with the theory. A Data Structure diagram (Figure 8) was created based on the hierarchical derivation of first-order concepts to second-order themes and aggregate dimensions which was consistent with the multi-layered model of Socio-Technical Systems (STS). These dimensions are subdivided into the Core Context, Technical and Social Subsystem, Socio-Technical Interactions, Circular-Economy Results, and Reflective and Forward-Looking layers, which depict the interplay of contextual, technological, and human factors in bringing sustainable transformation of the circular nature.

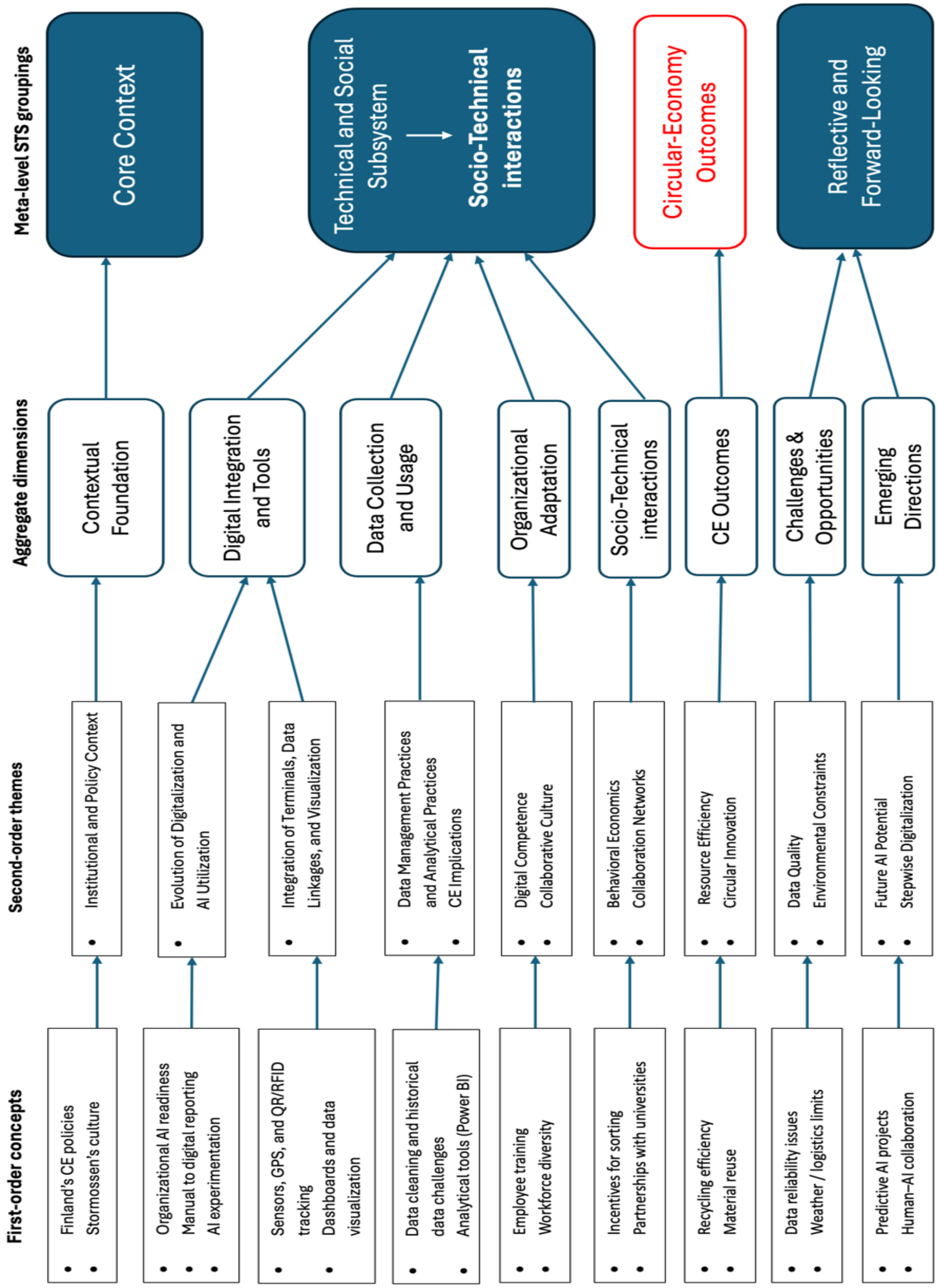

Figure 8: Data Structure of Thematic Analysis

Figure 8 represents the data structure that allows illustrating how themes were gradually abstracted because of the thematic analysis process. This framework connects the raw data with the theoretical foundations of the Socio-Technical Systems (STS) framework by demonstrating the interaction of the institutional, technical, and social facets to facilitate a joint optimization and produce the results of the circular-economy. The Challenges and Opportunities and Emerging Directions factor also contributes to the reflective and future-focused aspect and focuses on the adaptivity of learning and the innovativeness of digitalization through AI.

The last of eight themes arising out of this form is the content of the following chapter. Chapter 4 expands upon such themes in more detail, presenting the Thematic Map (Figure 9) that illustrates the cumulative impact of the socio-technical aspects of AI-enabled digital transformation on the aims of Finland towards a circular economy in the Stormossen case.

4. FINDINGS

4.1 Introduction

This chapter presents the data analysis and discussion of findings derived from the thematic analysis of interview, document, and observational data collected at Stormossen. The analysis follows Braun and Clarke's (2006) six-phase framework and is guided by the Socio-Technical Systems (STS) theory (Trist & Bamforth, 1951; Trist, 1981). It integrates empirical insights with theoretical and policy perspectives to explore how AI-driven digitalization advances circular economy (CE) objectives in Finland's waste management sector.

The chapter is organized around eight major themes: Contextual Foundation, Digital Integration and Tools, Data Collection and Usage, Organizational Adaptation and Learning, Socio-Technical Interactions and Joint Optimization, Circular-Economy Outcomes, Challenges and Opportunities, and Emerging Directions and AI Potential. Each theme is analyzed through the STS lens, emphasizing the interdependencies between technological tools (technical subsystem) and human, organizational, and cultural factors (social subsystem).

Together, these findings provide a comprehensive understanding of how Stormossen's digital initiatives enable CE goals through socio-technical alignment and innovation, addressing the research question: How does AI-driven digitalization contribute to CE practices in Finland's waste management sector?

4.2 Overview of Thematic Framework

Eight general themes were identified through thematic analysis in which each general theme had several subthemes accompanied by representative codes. The Thematic Map provided in Figure 11 describes the integration of these themes and reveals the overall course of the pathway of Socio-Technical Systems (STS) integration, between the contextual, technical, and social subsystems towards their mutual optimization and the results of a circular economy.

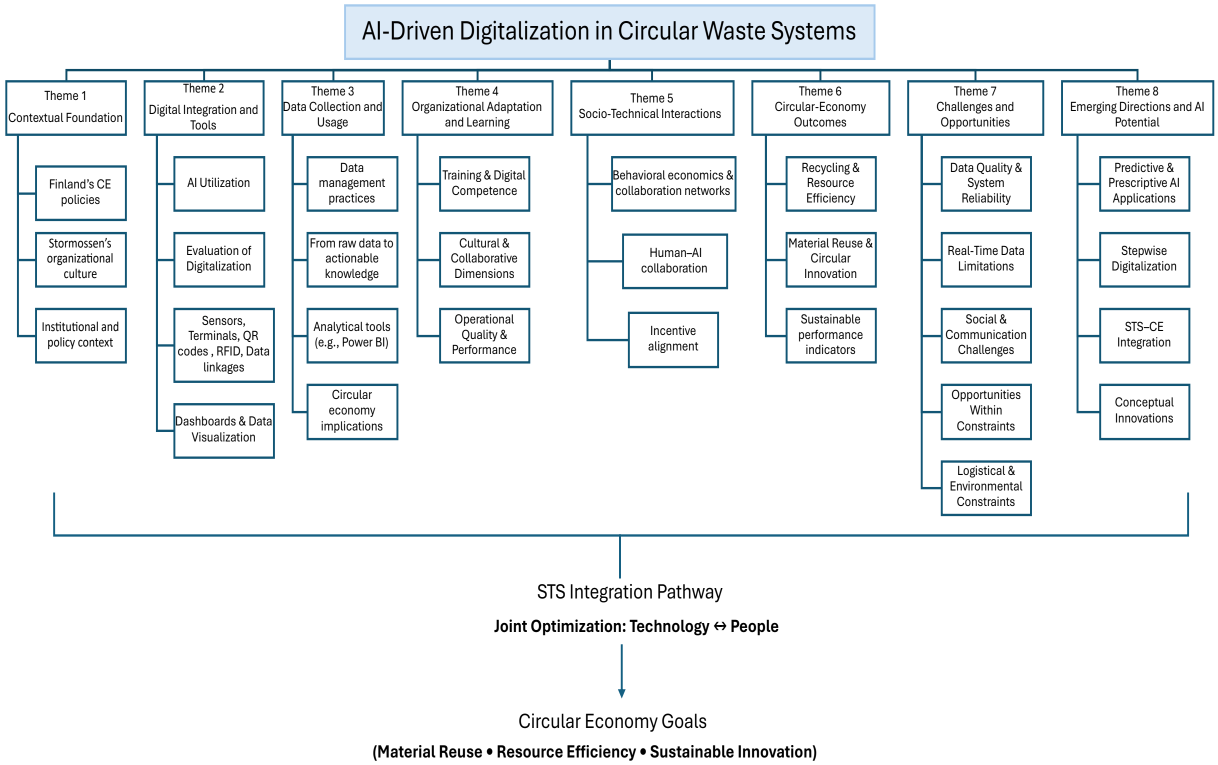

Figure 9 : Thematic map illustrating the main themes and subthemes derived from thematic analysis.

Figure 9 thematic map shows how the contextual, technological, organizational, and socio-technical factors act together to influence the digital transformation of Stormossen towards the goals of the circular economy. It focuses on the interactive fit between digital capabilities (technical subsystem) and human-organizational capabilities (social subsystem) that lead to joint optimization, which is one of the fundamental tenets of the Socio-Technical Systems framework. The Challenges and Opportunities and Emerging Directions and AI Potential add to the scope of the model by the reflective and prospective character of the innovation of AI-driven CE in Finland.

The given map is also aligned with a larger theoretical framework of STS and the Circular Economy Roadmap of Finland, which theorizes the systemic role of digitalization in ensuring sustainability, resource efficiency, and innovation (Ministry of the Environment, 2021; Peura et al., 2022). It gives the structuring rationale of Sections 4.3 to 4.10 wherein all the eight themes are discussed in detail with reference to evidence provided by interviews, document analysis, and observations of context.

4.3 Theme 1: Contextual Foundation

The contextual basis of the digital transformation of Stormossen is the overall policy setting of the Finnish circular economy, which may be both a regulatory framework and a driving force of innovation. As the findings suggest, technological and organizational development of the company cannot be perceived outside of its policy, institutional, and cultural setting. Respondents repeatedly stressed that at the national level, circular economy strategies, through the individual requirements of the municipalities, and mutually agreed norms, determine the way Stormossen executes the sustainability and digitalization efforts. This alignment demonstrates the socio-technical embeddedness of innovation where technology adoption is shaped by social values, governance systems, and cultural practices (Trist & Bamforth, 1951; Iden & Bygstad, 2025).

Through the national CE roadmap by Sitra, Finland has established itself as a world leader in switching to a circular economy. According to interviewees, there was a national focus on the efficiency of recycling, the traceability of waste, and carbon neutrality: *"Finland has a strong national strategy for circular economy; the policies guide waste companies like ours to reach high recycling and carbon-neutral targets. The 99% recycling goal is part of the EU and Finnish roadmap." (CF1).* The location of the company is a stimulus and a barrier to the local firms, such as Stormossen. The objectives of the company are coherent with the national and EU sustainability objectives, including minimization of waste, material reuse, and information transparency.

The policy framework, according to participants, requires digital tools to be used in reporting, traceability and environmental monitoring and data-driven accountability is integrated into daily operations. *"There is strict regulation about waste separation and* *reporting. Every municipal company must show traceability in data and transparency in logistics." (CF3).* In theoretical terms, this is an indicator of the alignment of the technical subsystem (digital tools, IoT, and automation) with institutional governance forms, which advances the notion that technological change in sustainability-oriented organizations is mediated by policies, and not necessarily solely by the market (Zhang et al., 2023; Motiva, 2024).

The internal culture of Stormossen proved to be one of the essential facilitators of digital innovation and implementation of the circular economy. The participants described the company as an open, collaborative, and learning oriented culture that appreciates inclusivity and involvement of employees in decision making, *"The company culture is very open and cooperative. We work in a flat hierarchy and everyone's opinion matters, even drivers can give suggestions on route improvements." (CF4)*. The participatory culture is consistent with the social subsystem of STS framework, in which empowerment and communication are essential during successful adoption of technology. Trust development and learning contribute to digital and sustainability transitions by enabling employees of all levels to participate in decisions and contribute to establishing flat hierarchies and distributed decision-making. This dynamic is like the results of Iden and Bygstad (2025), who observe that the social engagement and organizational learning are the most important predictors of digital maturity in the public-sector sustainability.

Furthermore, the presence of collaborative governance including partnerships with universities, municipalities, and private firms was repeatedly highlighted: *"We have close collaboration with cities, universities, and other companies; it's very Finnish to share data and work jointly on environmental solutions." (CF5)*

Such partnerships can be associated with the innovation culture of networks that Finland has developed, whereby, public-privately-funded partnerships encourage experimentation and learning that is essential in scaling circular economy initiatives. Other issues that were discussed by respondents are the institutional scaffolding that upholds innovation specifically funding mechanisms and legislative frameworks. Governmental and EU programs were identified as important sources of financial and strategic support for digital waste management pilots: *"The institutional setting is very supportive of digitalization. Funding often comes from government or EU projects focusing on smart waste management" (CF8)*. This systemic support allows the municipal companies to experiment with new technologies such as AI-assisted sorting or IoT-based route optimization, without incurring a significant financial loss. The socio-technical co-evolution model places the adaptive capacity as an essential element that is supported by the institutional context (Trist, 1981).

Finland has a wider society culture which also leads to the success of circular economy initiatives. According to the respondents, Finnish citizens tend to be highly environmentally conscious and recycle; however, more work is required to address the immigrant population: *"Local residents are generally very aware of recycling, but immigrants need more guidance; we try to educate them through multilingual campaigns." (CF6)*. This demonstrates how cultural inclusion and communication strategies form part of the social infrastructure required for technological systems to function effectively. In the STS lens, community engagement acts as the human interface of the digital system, ensuring that data-driven waste management aligns with actual user behavior and local needs. Finally, the data revealed that Stormossen possesses a strong innovation orientation, actively experimenting with emerging technologies such as AI and sensor-based monitoring: "Stormossen is quite forward-looking; we test new technologies before others, like AI pilots or bin sensors. It's part of the innovation mindset we have." (CF7). This proactive attitude toward innovation underscores the company's institutional agility, demonstrating how organizational culture and national policy frameworks jointly nurture digital experimentation within a sustainability agenda.

4.4 Theme 2: Digital Integration and Tools

Digitalization has already become a part of the life cycle of waste management at Stormossen, but there is insufficient implementation of AI. The digital tools applied by the company include GPS-enabled vehicle terminals, route optimization software, dashboards and waste tracking QR/RFID systems. As one of the participants stated, *"AI is primarily a venture of the future. Others are using GPT and Gemini, but not as a business tool"* (Code DIC1). This makes it clear that although digital infrastructure is highly advanced, the use of AI remains very dispersed, and it is largely utilized when addressing single problems, such as summarizing reports, but not automation at the organizational level. Theme 1 is also studied in four sub-categories: Evolution of Digitalization, Current AI Usage, Sensor, Terminal Integration and QR/RFID Connections, Dashboards and Data Visualization

The digital transformation process by Stormossen can be considered as part of a larger trend in Finnish waste management, as it is turning from manual operations to semi-automated and data-driven systems. According to the data collected during the interview, there is a linear process where manual reporting is followed by digital reporting and then automation and then AI-based analysis (Code ESFD1). This is in line with the gradual transformation toward digitalization outlined by Parviainen et al. (2017) as organizations move into digitization (conversion of analog data), digitalization (reorganization of processes using digital means), and finally digital transformation (reconstruction of business model based on technology). Dashboards are a significant innovation, although currently *"not utilized at Stormossen on a greater scale"* (DIC3). Their underuse indicates an opportunity to integrate AI-driven analytics for real-time decision-making. As Fang et al. (2023) observe, predictive dashboards can enhance efficiency in waste logistics by forecasting bin fullness and adjusting routes dynamically, an approach still in its infancy at Stormossen.

Findings reveal sporadic AI engagement across different operational levels. Employees mentioned *"tools such as Microsoft Copilot, Google Gemini, and cloud-based AI systems, primarily for data summarization, visualization, and documentation"* (DIC8). Although these tools demonstrate awareness of AI potential, their impact is limited due to the absence of formal policy and structured integration. In this context, Stormossen mirrors the early "experimentation stage" identified by Helo et al. (2021), where organizations pilot AI functionalities without embedding them in decision-making systems. According to the STS framework, this phase represents technological readiness without full social integration, a state where human-machine synergy is possible but unrealized.

Every vehicle at Stormossen has driven terminals (DIC2, TS1) which permit real-time communication between drivers and the control center. These terminals offer dropdown report formats to operational incidents in the form of overfilled bins or missed collections (DIC13). Besides that, the company is testing remote bin-level sensors to track collection points (DIC10, TS2). Although these technologies would ensure efficiency, vandalism (TS6) and reliability problems like battery breakdowns of sensors make it difficult to adopt these technologies uniformly. The vehicle GPS tracking systems are more developed. One of the managers said that *"we track vehicles and bin locations using GPS... RFID bins are not yet cost-efficient"* (DIC7). It means that there is a cost-benefit issue: automating work is effective, but investment and maintenance expenses discourage it. Muller et al., (2018) argue that early stages of digitalization usually imply trade-offs between economic viability and technological advancements, a conflict that is observed at Stormossen.

Stormossen's use of QR code-based customer cards and RFID tags (DIC4, TS3) represents a key enabler of traceability and accountability in waste collection. These systems link transfer documents with unique identifiers, allowing data flow between transport companies, weighing facilities, and internal dashboards. This digital traceability supports CE objectives by providing transparent tracking of waste movements, a prerequisite for material flow analysis and recycling optimization (European Commission, 2020). However, the current limitation lies in the lack of real-time synchronization between platforms, a constraint that restricts AI from processing data autonomously for predictive logistics. The participants explained that *"there were several digital dashboards, which were divided into operational, tactical, analytical, and strategic"* (DIC3). However, they have not been exploited to their fullest capabilities and are used in retrospective modes and not predictive ones. This is what Helo et al. (2021) define as the informational ceiling, where digital products are already there but are not used or fully employed as a source of transformative insight because of a lack of data literacy or the absence of AI integration. According to the perspective of STS, such a gap indicates sub-optimization: the technical subsystem (software tools) has been developed more rapidly than the social one (skills, routines, and decision norms). This does not happen, as Trist (1981) stressed, until both systems co-evolve with each other because of joint optimization coupled with human judgment and machine analytics.

The results show that there was a partial convergence between social adaptation and technological development at Stormossen. Although the digital infrastructure, including sophisticated GPSs, vehicle terminals, RFID solutions, and data platforms, has already reached a comparatively high degree of maturity, the processes of people and the organization are still adapting to this level. Employees are only partially educated about AI applications, and the level of fear of automation is present, which reduces the use of digital analytics in operations in an ad-hoc manner. According to the STS theory, this inequality hinders the ability to work. Trist and Bamforth (1951) argued that when technological processes are introduced without social restructuring, productivity gains are diminished by reducing work quality and participation.

In Stormossen, similar processes occur where digital tools are available but require the restructuring of social processes and decision-making. Digital integration plays a role in the performance of the circular economy in several practical aspects. The RFID and QR systems improve waste flow tracking by making it more traceable and transparent, which is necessary to bridge material loops (Gonzoalmez-Sanchez et al., 2023). By minimizing the distance of travel and use of fuel, GPS route optimization enhances efficiency in operations that support the objectives of the circular economy minimizing the environmental impact. Moreover, computerized past data enhances the availability of data, making it possible to plan recycling and reuse programs based on evidence. Nevertheless, opportunities of AI, like predictive analytics to plan the route or robotic sorting to recover materials, are yet to be actualized. This observation is also supported by Fang et al. (2023), who observe that AI has the potential to minimize logistics expenses by up to 13% when implemented in waste systems completely. The basis of such integration can be found at Stormossen, yet it is not implemented, but rather an idea.

4.5 Theme 3: Data Collection and Usage

The digital transformation of Stormossen is embedded in the capacity of the company to gather, store and use quality waste data. The repositories of the company cover *"more than 30 years of the history, and the last seven were completely digitized and traceable"* (DCU1). These datasets also include indicators of incoming waste weights, customer codes, and bin-level reporting, which are the basis of the analytical support of operational and environmental decision-making. According to the participants, data intelligence is the foundation of a successful performance of a circular economy, and that the material flow, knowledge, and analysis are crucial to that (DCU3). The comprehensive nature of Stormossen data enables long-term monitoring of waste separation practices, efficiency and rapid cost optimization. Theme 2 will be analyzed in four categories, which include Digital Tools and Analytical Practices, From Raw Data to Actionable Knowledge, Socio-Technical Interpretation and circular economy Implications. Stormossen uses a variety of digital tools to support data management, including Power BI dashboards, Project TOP, and an in-house developed computational unit (DCU4). These tools enable the monitoring of processes across wastewater and local systems. Furthermore, participation in the national "recycling computational tool" project demonstrates strong alignment with Finland's environmental and social stewardship principles (Ministry of Environment, 2021).

Although this has been achieved, a respondent has also indicated a recurrent problem of data fragmentation and manual preprocessing. One employee noted that *"the raw data* *itself is quite messy... you have to do a lot of manual work to clean it up"* (DCU9). The other one has also said that he used a hexadecimal-based search to correct undocumented flaws (DCU10). This brings out the human cost of data curation, which cannot be underestimated because inconsistent data formats and high lack of automation. Helo et al. (2021) also note that in early stages of digital maturity, organizations tend to experience so-called data cleanliness debt wherein significant amounts of time are spent on data validation at the expense of generating insights. This debt, at Stormossen, limits the whole application of analytics to forecasting or insights with the help of AI.

The transition from data accumulation to knowledge creation is crucial. One manager noted that integrating datasets *"saved 40,000 euros in effectivizing logistics last year"* (DCU8), demonstrating that data-driven logistics not only generate economic and environmental value by enhancing resource efficiency and lowering emissions but also save costs. Stormossen has yet to reach the stage of predictive or prescriptive AI-driven analytics, as despite having a formidable analytical infrastructure, it remains predominantly at the descriptive level (Fang et al., 2023). The data system is a technically robust yet socially inefficient system from an STS point of view. Although this can be aided by advanced tools that facilitate storage, visualization, and access, much of the analysis relies on a small group of experts cleaning data, implying that there is limited analytical competence diffusion in an organization. The outcome of this imbalance is partial joint optimization (Trist, 1981). The quality of data has a high impact on the recycling rates and the accuracy of the circular economy reporting; well-integrated clean data enhances Life-Cycle Assessment (LCA) and has the capacity to inform targeted community education through demographic insights (DCU6).

4.6 Theme 4: Organizational Adaptation and Learning

The adoption of digital tools has required organizational learning and cultural change. Participants consistently highlighted training, repetition, and ongoing improvement as vital success factors. One respondent stressed that *“the mother of all schooling is repetition, repetition, check, repeat”* (OAL3), demonstrating the company’s pragmatic learning culture. Theme 3 is explored through four subcategories: Training and Digital Competence, Cultural and Collaborative Dimensions, Operational Quality and Performance, and STS Interpretation. Stormossen provides regular training sessions on segregation standards and tool usage (OAL1, OAL7).

Nevertheless, multiple participants gave the workforce engaged in varying digital literacy, as they were at ease with new systems. According to one interviewee, *“some fears... they fear that if there come efficient tools... they lose their job”* (OAL4). This response is parallel to the findings provided by Parasuraman and Wickens (2008), who define the feeling of automation anxiety as one of the obstacles to technological acceptance. It is necessary to discuss these fears by means of open dialogue that will present AI and automation as ways of extending, not substituting, technologies.

The presence of a multicultural population in Stormossen is both a workforce and customer-based environment that brings about a complex linguistic and cultural environment. Employees and residents belonging to various cultural backgrounds react differently to communication styles as they observed (OAL2). This observation is like Hofstede’s (2011) cultural dimensions theory, which argues that the national culture shapes uncertainty tolerance to innovation. Positively, the culture of internal collaboration of the company seems to be high: *“Continuous learning... collaboration is the main one”* (OAL5). This supports the development of learning organizations (Senge, 1990), where feedback loops foster both individual and collective competence.

Digitalization has also enhanced the quality of operations as one of the respondents noted: *"When we started 2½ years ago, it was terrible... nowadays quality is quite good"* (OAL6). This development demonstrates the effect of the learning curve, in which repeated use of digital tools improves performance (Argote, 2013). Nevertheless, a significant part of training is still reactive, which does not allow being ready for advanced AI systems. The socio-technical perspective would be enhanced by incorporating digital literacy as a key competency. Regarding the STS, the social subsystem being analyzed by Stormossen is progressing toward digital maturity with certain resistance and unequal skills, which makes it necessary to ensure balanced technological and human progress.

4.7 Theme 5: Socio-Technical Interactions and Joint Optimization

The central idea of STS theory is the notion of joint optimization which is the concomitant improvement of social and technical subsystems to achieve sustainable performance (Trist and Bamforth, 1951). In the case of Stormossen, joint optimization is realized in the form of digital platforms and multilingual outreach and incentive mechanisms that connect human behavior to the technological systems. Theme 4 is discussed in four subcategories: Digital Social Interfaces, Incentive Alignment, Behavioral Economics, Collaborative Networks and Partnerships and STS Interpretation. Stormossen offers three language sorting instructions (JOTA3) in its mobile app, which also contributes to the solution of the linguistic diversity problem. The participants recommended that *"this be extended to an intermediate application to the immigrant communities"* (JOTA2). Through this, it means that the design thought of user-centered digital inclusion is aligned with the principles of participatory design that were set forth by Ehn (2008). The latter applications can be used to illustrate the correspondence of the technical and social subsystems: technology is an intermediary that improves social communication, whereas social feedback helps in the further optimization of an app.

To encourage sorting behavior, the company uses financial incentives and penalty systems: *“If you don’t want to segregate, don’t segregate. You just pay four times more”* (JOTA4). This reflects the nudge theory (Thaler & Sunstein, 2008), where it is not forced, but those behavioral changes are promoted by subtle economic instruments. In an STS perspective, this is a joint- optimization at the boundary between social policy and digital infrastructure: pricing algorithms, billing databases and user behavior mutually reinforce each other to enforce compliance with circular economy. Internet connections with technology companies and universities also help in the pursuit of joint optimization (PC3, PC5). The Vaasa University data harvesting project is an example of how social collaborations lead to the creation of technical innovation. This kind of collaboration creates a socio-technical network (Bijker et al., 2012) in which the exchange of knowledge leads to continuous improvement. Stormossen’s social analysis shows that digital transformation is successful when it is designed with employees and organizations in mind. The shift from isolated technological advancements to collaborative ecosystem-based collaboration demonstrates a mature STS connection. However, maintaining this balance requires ongoing dialogue and shared governance mechanisms to prevent technological drift or societal disruption.

4.8 Theme 6: CE Outcomes

Stormossen digitalization is a direct contributor to the circular economy goals in Finland as it enhances recycling, material reuse, and optimization of the logistics. The respondents often associated data management and AI preparedness with the results of the circular economy and claimed that *“material flow, knowledge, and analysis are crucial for a successful circular economy”* (CEO1). Theme 5 is examined under three subcategories: Recycling and Resource Efficiency, Material Reuse and Circular Innovation and STS Interpretation. Stormossen’s high recycling rate (98–99%) is due to effective data analysis, digital road design and citizen participation. *“We have developed a recycling calculation tool”* (CEO3) enables the quantitative assessment of environmental progress, in line with EU tax rules (European Commission, 2020). Logistics data is being analyzed to reduce unnecessary trips and promote car use (LRP6-LRP7). According to González-Sánchez et al. (2023), such digital optimization can reduce CO_2 emissions by 10–20%, highlighting the tangible environmental benefits of socio-technical integration.

Participants talked about projects that were exploring material reuse in partnership with municipalities, such as biowaste into local fertilizers (CEO4). The implementation of these initiatives reflects systemic circular economy thinking, in which digital traceability makes compliance and transparency mandatory across material cycles. The potential contribution of AI has not yet been actualized, but it is still in its infancy. Respondents had high expectations that *"AI will, or rather must, be used in the future"* (CEO2). Applications expected are automated waste-flow forecasting and robotic sorting (DIC9). These developments would propel Stormossen out of an operational circular economy stage (efficiency-oriented) to a strategic circular economy stage (innovation-oriented), as identified by Kalmykova et al., (2018). Regarding the STS perspective, circular economy outcomes are the observable outcomes of well-adjusted socio-technical performance. Human behaviors, digital systems, and regulatory frameworks work well together, resource loops become narrow and environmental externalities are reduced. The success of Stormossen highlights the fact that the success of using circular economy does not only rely on technology, but also on the capacity of the organization to interpret, translate and respond to digital intelligence.

4.9 Theme 7: Challenges and Opportunities

Although there has been significant advancement in terms of digital integration, the digital transformation maintained by Stormossen is still affected by technical, organizational, and contextual challenges. Although limited to short-term efficiency, these challenges also display the potential to achieve focused enhancement and innovation. The primary constraints identified through thematic coding include (a) unreliable sensors, (b) messy or incomplete data, (c) social communication gaps, and (d) logistical disruptions caused by external conditions such as weather or urban congestion. Theme 6 is examined under six subcategories: Data Quality and System Reliability, Real-Time Data Limitations, Social and Communication Challenges, Logistical and Environmental Constraints, Opportunities within the Constraints and STS Interpretation

Participants often identified data errors as a barrier to automation efforts. *"The raw data itself is quite messy... you have to do a lot of manual work to clean it up"* (CO5). This issue, previously mentioned in Theme 2, resurfaces here as a systemic problem hindering AI applications. Incomplete data records hinder the development of predictive models, leading to what Kitchin (2014) calls a data mismatch conflict between digital demand and actual data availability. Sensor reliability was also cited as a concern: *"The batteries run out, or someone is breaking it down... it just gets destroyed"* (CO6). This is a demonstration that technological infrastructures are still susceptible to the environment and human factors, requiring a stronger sensor design or a hybrid verification approach. The same can be said in Fang et al., who discovered that monitoring waste using IoT frequently fails in very Nordic conditions (2023).

The unavailability of real-time data was another theme that came up. One participant lamented, *"Unfortunately... we really don't have enough real-time data"* (CO7). This delay reduces the ability to adjust routes or predict human levels, leading to poor resource allocation. Real-time integration not only increases efficiency but also enables AI to create adaptive scheduling, a hallmark of the evolving smart supply chain (González-Sánchez et al., 2023). From the social subsystem perspective, information accessibility and communication remain problematic. *"The information probably hasn't gone out properly. Maybe there is some pamphlet somewhere... that no one ever sees"* (CO2). Likewise, social media engagement metrics remain low: *"600 followers, 1,400 visits, nothing, like zero"* (CO3). These observations show that digital communication approaches must shift towards the broadcast model towards interactive communication with the use of mobile platforms and multilingual content to make them inclusive.

Examples of the physical obstacles that were determined to be persistent included snow, blocked bins and vehicle access barriers (CO4). These realities of the environment are a reminder that digitalization can never overcome material constraints but can reduce them by means of predictive planning and flexible routing systems. Each of these challenges simultaneously represents an opportunity. Data cleaning promotes the use of AI-aided data governance. Issues of reliability of the sensor encourage R&D collaborations of sustainable smart devices, and Low engagement levels indicate that the company should focus on social innovation, that is, incorporating gamification or incentive-based sorting applications.

Thus, Stormossen's digital evolution follows what Luhmann, N. (1995) called functional differentiation; each new subsystem (technical, social, ecological) develops complexity that generates both problems and solutions. Under the lens of STS, the digitalization of Stormossen is at a dynamic balance, where technical system is developed and limited to the adaptation of the social environment and the environment. This partial correspondence implies the necessity of iterative redesign and not wholesale change, ongoing, participative improvement involving user feedback, validation of data, and inter-organizational learning.

4.10 Theme 8: Emerging Directions and AI Potential

The participants were very prospective, speaking about new technologies and future perspectives using AI. These stories demonstrate the organizational receptivity to innovation and progressive vision in the field of automation in various spheres of operations. Theme 7 is examined under five subcategories: Predictive and Prescriptive AI Applications, Human–AI Collaboration, Stepwise Digitalization, Conceptual Innovations and STS and CE Integration.

It is imagined that AI can increase the accuracy of waste flow forecasting, optimize logistics, and sort automatically. According to one of the respondents, *"AI could help with predictive analysis forecasting flows or optimizing logistics"* (ESFD6). These ambitions align with the prescriptive analytics phase mentioned by Davenport and Harris (2017), in which AI does not only interpret data but also suggests decisions. The leadership at Stormossen has realized this potential, but they recognize infrastructural gaps. The preparation of AI necessitates clean and standardized data, connectivity between sensors, and trust among the employees, which are gradually being developed. Participants frequently highlighted the importance of maintaining open-mindedness toward digital change (ESFD7). This feeling corresponds to the contemporary socio-technical paradigms of augmented intelligence (Wilson and Daugherty, 2018), which suggest collaboration instead of replacing humans and machines. As part of the staff functions, AI is not expected to remove its functions, which include route management, recycling analysis, and environmental reporting.

One interviewee summarized Stormossen's digital trajectory succinctly: *"Manual reporting → digital reporting → automation in reporting → AI or similar analysis"* (ESFD1). This fact can be attributed to the evolutionary trend of the digital maturity of the organization and is in line with the gradual innovation framework suggested by Parviainen et al. (2017). Instead of implementing disruptive changes, Stormossen has proven to be a step-by-step method with each technological advancement defining the next level of development. Several creative ideas emerged from this progression, including mobile applications designed for immigrant users to facilitate communication between collection companies and residents (ESFD3), gamified advertising campaigns that promote the message *"waste is money"* (ESFD4), and button-based bin fullness reporting systems to enable quick digital feedback (ESFD9).

These initiatives illustrate a practical and participatory approach to digital innovation, where user engagement complements technological growth. These illustrate grassroots innovation employee-driven ideas reflecting social embeddedness rather than top-down directives. In STS terms, these micro-innovations are essential for achieving bottom-up alignment between technological design and social context (Ehn, 2008). From the perspective of STS theory, Stormossen's emerging AI vision embodies joint optimization in progress: technical infrastructures are prepared, and the social system is conceptually ready, though not yet operationally synchronized. From a CE standpoint, these innovations promise future efficiency, traceability, and community empowerment.

4.11 Linking the Findings to the Conceptual Framework

The findings of this study are very much related to the relationships that are depicted in the conceptual framework (Figure 8). The framework, which is based on the Socio-Technical Systems (STS) theory, puts the policies of Finland, the organizational culture of Stormossen, and the roadmap of the national circular economy as the contextual background that determines the interaction between the technical and social subsystems. The digitalization of the above forms through the integration of these subsystems yields the desired results of a circular economy, including resource efficiency, waste reduction, and sustainable innovation. The empirical expression of this theoretical model is the eight themes which were identified in the thematic analysis.

Theme 1 – Contextual Foundation creates the institutional and policy context of the digital transformation of Stormossen. The enabling environment of adoption of AI and circular practice is formed by the circular economy policies of Finland and Stormossen culture, which is sustainability oriented.

Themes 2–3 – Technical Subsystem, the themes Digital Integration and Tools and Data Collection and Usage represent the technical dimension of the framework. They demonstrate how technologies such as GPS, RFID, QR tracking, dashboards, and analytics digitally streamline waste management processes, providing data-driven insights and improving decisions. These provide the digital infrastructure that supports AI optimization. However, according to STS theory, technological advancements alone do not lead to improved performance; societal change must also occur.

Themes 4–5 – Social Subsystem and Socio-Technical Interactions, The human and organizational aspect is represented in terms of Organizational Adaptation and Learning, which is concerned with training employees, collaborative culture, and digital competence. Socio-Technical Interactions occupies the middle of the framework and describes the interaction between people and technology based on incentives, behavioral mechanisms and cross-sector partnerships. This constitutes the principle of joint optimization in which the effectiveness of the system is a result of the co-evolution of both social and technical aspects of the system.

Themes 6–8 – Circular-Economy Outcomes and Future Orientation. Circular-Economy Outcomes, Challenges and Opportunities, and Emerging Directions and AI Potential correspond to the outcome and forward-looking dimensions of the framework. They show how the socio-technical alignment can produce quantifiable outcomes like resource efficiency, material reuse and sustainable innovation, and expose the ongoing issues like data reliability and limits of integration. The last theme, Emerging Directions and AI Potential, views the framework into the future and demonstrates how predictive analytics, human-AI cooperation, and gradual digitalization may further improve system intelligence and maintain the further development of circular economy.

Taken together, these eight themes trace the STS integration pathway articulated in the framework:

Contextual Foundation → Socio-Technical Interactions→ Circular-Economy Outcomes.

This pathway clearly demonstrates that AI-driven digital transformation drives continuous progress when technological infrastructure, human capabilities, and institutional conditions evolve together. Therefore, the findings support the main idea of this study: The interaction of human and technological interactions is a process of digital transformation that enables sustainable circular economy performance.

5 DISCUSSION

5.1 Theoretical Implications

This study advances the understanding of AI-driven digitalization within the framework of Socio-Technical Systems (STS) and the Circular Economy. It demonstrates empirically that organizational sustainability outcomes arise not solely from technological adoption but from the dynamic interaction between digital infrastructures, human behavior, and institutional context.

First, the findings confirm and extend Trist and Bamforth’s (1951) argument that optimal organizational performance emerges when social and technical subsystems co-evolve. At Stormossen, digital tools and AI applications enhanced operational visibility, but their transformative potential was realized only through staff learning, participatory reporting, and cross-functional collaboration. This integration introduces the concept of a digitally augmented STS, in which AI functions as an intermediary translating data into actionable human knowledge.

Second, the results contribute to CE theory by empirically validating that digitalization acts as an enabler of circular performance (Peura et al., 2022; Fang et al., 2023). When technical traceability systems and social engagement mechanisms align, waste flows become transparent, and resource loops close more efficiently. This finding bridges data intelligence and material intelligence, offering a theoretical link between digital transformation and circular sustainability.

Third, the study enriches the emerging literature on AI and sustainability transitions by revealing that AI adoption follows a gradual, relational trajectory—driven by experimentation, learning, and trust. This supports Wilson and Daugherty’s (2018) concept of collaborative intelligence, where human insight and machine capability mutually enhance one another.

Finally, the study contributes a conceptual model of the STS integration pathway, which connects the contextual foundation, technical and social subsystems, and circular-economy outcomes through Socio-Technical Interactions. The model emphasizes that digitalization, when guided by socio-technical alignment, transforms waste management into a circular, intelligent, and participatory system. this research advances STS theory by integrating environmental sustainability into socio-technical reasoning and extends circular economy theory by positioning AI-driven digitalization as a mechanism of systemic learning and adaptive transformation.

5.2 Managerial Implications and Practical Solutions

The study provides practical guidance to managers and policymakers seeking to digitalize waste management processes in alignment with the circular economy objectives. Based on empirical evidence, there is a three-phase step-by-step digitalization framework that will be presented, which will provide a low-cost, scalable, and human-centered transformation.

Short-Term (Operational Digitalization Phase)

Simple and low-cost applications should be used by managers as the beginning, which will gradually become more visible and efficient. QR codes or mobile reporting applications enable drivers to upload the information regarding traffic jams, roadway situations or pollution incidents directly on the dashboard of their vehicle or smartphone. This real-time data capture creates accountability and power for the frontline workers, which puts the STS principle of Collaboratory design into practice (Ehn, 2008)

The main management measures involve implementing digital forms for field reporting in the already existing Office 365 or Teams platforms, appointing the role of digital champions to teach colleagues and ensure the data remains consistent, and creating a feedback system to demonstrate to employees the effects of their digital contribution. These steps are supposed to improve the speed of communication, decrease the use of paper-based procedures, and improve the level of staff membership in the digital tools.

Medium-Term (Integration and Data-Driven Management Phase)

The next step involves integrating disparate data sources into a centralized digital dashboard using Power BI or compatible open-source software. This integration combines vehicle data, logbooks, and route information to generate key performance indicators (KPIs) such as overall performance, throughput, and recycling rates. Establishing data governance standards for accuracy, interoperability, and security is critical.

At the same time, the managers are to integrate ongoing training opportunities that can assist the employees in understanding the analytics and utilizing the data insights in decision-making. This is an expression of the principle of joint optimization (Trist, 1981) where the technology and human competence evolve in such a way that it improves the performance of the organization. To enable this integration, managers could create an internal digital analytics center to manage the dashboards and data quality, arrange cross-departmental workshops devoted to the interpretation of key performance indicators (KPIs), and implement dashboards in the daily briefing and performance review. Such measures are likely to enhance managerial effectiveness, reduce redundancy, and allow for the realization of inefficiencies early stages, therefore, reinforcing data-driven decision-making and contributing to the efficient circular economy monitoring.

Long-Term (Predictive and AI-Enhanced Phase)

When basic data systems are fully developed, Stormossen can be enhanced to AI-based predictive management. The implementation of the IoT bin sensors, machine-learning algorithms and automatic trading routes optimization will allow flexibility in time and finding anomalies before they occur. Research and development of energy-harvesting sensors and AI-based sorting robotics should be furthered in accordance with the creation of strategic collaboration with universities and technology companies.

The role of humans should also be changed simultaneously: the staff should be retrained to perform analytical, supervisory, and decision-support duties, so that AI is not aimed at replacing. Concentrating on piloting predictive analytics to optimize routes and foresee waste, ensuring AI ethics and data privacy principles, and integrating environmental KPIs, like CO2 savings, in AI performance dashboards, Stormossen would be a good move. Such measures are likely to cut expenses and emissions, increase proactive planning, and increase national contributions to circular economy. Along with the step-by-step method, this strategy emphasizes that digital transformation is a learning process that can contribute to sustainable growth, involvement of workforce, and links digital progress to the aims of the circular economy.

5.3 Suggestions for Future Research

Although this study provides a comprehensive qualitative analysis, several directions remain open for future investigation. First, future studies should conduct quantitative evaluations of AI impact using longitudinal or quasi-experimental designs to quantify how AI-based route optimization and robotic sorting affect cost savings, emission reductions, and recycling rates. The second is Comparative and cross-cultural studies across Finnish or Nordic waste-management firms would clarify how organizational culture and policy frameworks influence digital maturity and socio-technical adaptation. Third, scholars should further examine Ethics, trust, and human–AI interaction, particularly how transparency, algorithmic accountability, and perceived fairness shape employee acceptance of AI in sustainability contexts. Fourth, Fourth, system-dynamics and digital-twin modelling approaches could be used to simulate long-term feedback loops between data infrastructure, human behavior, and circular economy outcomes under varying automation scenarios. Finally, the Socio-Technical Systems theory itself should be expanded for sustainability, integrating environmental indicators such as carbon intensity and resource circularity into the framework to advance the concept of green socio-technical systems.

5.4 Limitations

Several methodological and contextual constraints characterize the study. To begin with, the study takes a one-case focus, which is all about Stormossen. As a result, the results might not be personally applicable to other areas or waste-management systems that are governed under a different system or technological framework. Second, qualitative focus of the study, with its predominant use of interviews and document analysis gives more attention to comprehension than statistical generalization. In this way, the causal links between digitalization and the results of the circular economy are not factual but rather subjective. Third, the possibility of interpretive bias may not be completely excluded. Although the study was coded systematically, triangulated, and reflexively aware, there was a likelihood that the analytical lens of the researcher could have contributed to the focus given to some of the themes. Fourth, technological development creates a time constraint. Considering the sheer rate of development of AI and IoT tools, the real-world examples presented as part of this 2025 study, including one of Copilot or Gemini, are time-based and can be validated later.

Finally, access to internal financial and proprietary systems was limited by confidentiality, restricting the ability to quantitatively validate some findings. These limitations should be taken into consideration because the study will be more transparent, and more extensive mixed-method and cross-case studies are essential. In this chapter, there is a combination of empirical findings, theoretical and practical insights. Theoretically, it leads to the development of the Socio-Technical Systems (STS) and Circular Economy by showing that the implementation of AI-based circularity is not a result of technology per se but rather co-evolution between socio-technical systems. In practice, it provides a three-step digitalization roadmap, such as QR-code reporting to predictive AI applications that can be used to improve operational efficiency, inclusivity, and sustainability. The research finds that AI-based circular systems have an inherently circular, participatory, and human-oriented path to study.

Finally, the results suggest that the digitalization of processes based on AI makes possible the appearance of circular results not by technologies themselves but by mutual optimization of human and technical systems. This socio-technical cooperation brings organizational flexibility, transparency, and resource efficiency in the context of the circular economy in Finland and proves that sustainability is an outcome of the constant teamwork between individuals, processes, and smart technologies. The combination of theoretical knowledge with practical use allows developing the study and supporting the change in the comprehension of digital circularity as an evolving transformation and participation, which will be of academic value and practical advice to the ongoing sustainable innovation.

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Appendices

Appendix 1. Interview Questions

1. Management

a. AI and Digital Tools (Dashboard + Smart Systems)

I. What kinds of AI or digital tools are currently used at Stormossen?

II. Are any tools connected to real-time data like truck routes, bin fill levels, or sorting?

III. Do you use any dashboards to support daily operations or decision-making?

IV. Have you tried any low-cost tools like QR codes or manual data entry as a step toward automation?

b. Data Usage and System Integration

I. What type of data does Stormossen collect, most likely waste volumes or truck locations?

II. How is this data used to improve daily planning or reporting?

III. What platforms do you use internally (e.g., Teams, Excel, Power BI)?

IV. Would it help if staff could report bin levels via phone or QR code and view them all in one place? dashboard?

c. CE& Sustainability Impact

I. How do digital tools help you with your recycling, reuse, or sustainability targets?

II. Are there any AI or data projects that made a big impact on your circular goals?

III. How do you track progress on recycling or waste reduction with data?

d. Organizational Change and Staff Involvement

I. How have digital tools changed how your team works day to day?

II. What kind of training is needed to help staff use these tools confidently?

III. Can workers like drivers or sorters help report bin status using a simple tool?

IV. Would QR codes or posters near bins help staff or citizens sort more accurately?

e. Ecosystem & Partnerships

I. Do you work with other companies, cities, or universities on digital projects?

II. How important is external help (like EU funding or tech partners) for digital innovation?

III. Are there any shared platforms or pilot projects you've joined recently?

f. Challenges and Policy Environment

I. What challenges have you faced with AI or digital tools (e.g., cost, training)?

II. Do government or EU rules help or slow down your work with digitalization?

III. What are your future plans for using AI or data at Stormossen?

IV. Do you think it makes sense to start with manual reporting and move slowly to AI?

2. Operations and Logistics/ Frontline Staff – Joint Interview

a. Daily Operations & CE Contribution

I. Can you describe your role in Stormossen's daily logistics and collection operations?

II. How does logistics support Stormossen's recycling and CE goals?

III. What are the most common challenges you face during collection or transport?

b. Digital Tools & Route Planning

I. What digital tools or systems do you use in your daily work (e.g., vehicle terminals, GPS, route planning tools)?

II. How are collection routes planned and optimized currently?

III. Do you use real-time data (e.g., bin levels, traffic info) to adjust routes?

c. Communication & Data Use

I. How do you report or receive information about collection (e.g., full bins, problems)?

II. Are drivers able to send data directly from the vehicle terminals?

III. How is the data from logistics shared with other teams (like sorting or management)?

d. Digitalization & Improvement Opportunities

I. What works well with the current systems, and what doesn't?

II. Do you think adding simple tools like QR codes or apps would help improve reporting or efficiency?

III. What kinds of future digital tools or AI (like predictive route planning) could support logistics?

3. Sorting and Recycling Facility

a. Role in Circular Economy

I. What role does Stormossen's sorting and recycling facility play in supporting Finland's CE goals?

II. Which types of waste are the most challenging to sort and recycle here?

b. Current Technology & Automation

I. What sorting or recycling technologies are currently used in the facility (manual, semi-automatic, robotic, etc.)?

II. Have automated or digital tools (e.g., scanners, conveyor sensors, robotic sorters) improved the sorting process? If yes, how?

III. What limitations or problems do you face with the current technology?

c. Efficiency & Data Use

I. How do you measure or track the efficiency of sorting and recycling processes?

II. Is data (e.g., material types, contamination levels) collected from the facility? If yes, how is it used?

d. Future Digitalization & AI

I. What improvements or new technologies could make sorting and recycling more effective in the future?

II. Could AI, robotics, or advanced sensors help improve recycling efficiency Or reduce contamination?

III. What barriers (e.g., cost, training, maintenance) might prevent adoption of more advanced sorting technologies?

4. Data and IT Systems

a. CE & Operations

I. How does Stormossen support Finland's CE goals?

II. What are the main recycling and recovery methods you use?

III. How important is citizen participation, like household sorting, for your work?

IV. What are the biggest challenges you face in waste management today?

V. Where do you see the main opportunities for Stormossen to improve in the future?

b. Digitalization & Data

I. What digital tools or systems do you currently use in waste management?

II. What kind of data do you collect most often, and how is it used?

III. How do digital tools and data help your daily work?

IV. What challenges do you face with data or digital systems?

c. Future Digitalization & AI

I. Could new digital tools or AI help Stormossen in the future? If yes, how?

II. What barriers make it difficult to adopt more advanced digital or AI tools?

III. What steps could strengthen Stormossen's digitalization in the coming Year?

Appendix 2. Interviewees' Summary

Interviewee number	Department / Role	Type of organization / Unit	Date(s)	Length of the interview
1	**Management**	Public organization (Stormossen – Head office)	24 July 2025 & 5 Sept 2025	1h 22m
2	**Operations & Logistics / Frontline Staff (Joint Interview)**	Public organization (Logistics division)	13-Oct-25	31m 13s
3	**Sorting and Recycling Facility**	Public organization (Recycling plant)	2-Oct-25	38m
4	**Data and IT Systems**	Public organization (Stormossen – Head office)	2-Oct-25	1h 25m 42s

Appendix 3. Thematic themes and codes

Theme	Code Name	Code No.	Full Verbatim Description (from Transcript)
Contextual Foundation	Finland's Circular Economy (CE) Policies	CF1	"Finland has a strong national strategy for circular economy; the policies guide waste companies like ours to reach high recycling and carbon-neutral targets. The 99% recycling goal is part of the EU and Finnish roadmap."
Contextual Foundation	Policy Alignment with Municipal Goals	CF2	"Stormossen's work directly supports the Finnish CE roadmap; most of our projects come under the national targets for waste reduction and resource reuse."
Contextual Foundation	Institutional Support and Legislation	CF3	"There is strict regulation about waste separation and reporting. Every municipal company must show traceability in data and transparency in logistics."
Contextual Foundation	Stormossen's Organizational Culture	CF4	"The company culture is very open and cooperative. We work in a flat hierarchy and everyone's opinion matters, even drivers can give suggestions on route improvements."
Contextual Foundation	Collaborative Governance	CF5	"We have close collaboration with cities, universities, and other companies; it's very Finnish to share data and work jointly on environmental solutions."
Contextual Foundation	Community and Public Engagement	CF6	"Local residents are generally very aware of recycling, but immigrants need more guidance; we try to educate them through multilingual campaigns."
Contextual Foundation	Innovation Orientation	CF7	"Stormossen is quite forward-looking; we test new technologies before others, like AI pilots or bin sensors. It's part of the innovation mindset we have."

Contextual Foundation	Institutional and Policy Context	CF8	“The institutional setting is very supportive of digitalization. Funding often comes from government or EU projects focusing on smart waste management.”
Digital Integration and Tools	Vehicle Terminals and Sensors	DIC2	"All vehicles are mandated to have a drive-terminal in the vehicle. TCS or Vingo Logistic are our choice but also other are used. We are testing remote bin level sensors for remotecollection points."
Digital Integration and Tools	Dashboards Types	DIC3	"There are four types of dashboards: operational, strategic, analytical, and tactical. Not utilized atStormossen on a greater scale."
Digital Integration and Tools	QR Codes and RFID	DIC4	"Our customer card/app is QR code based. Transport companies use QR-codecards, RFID-tags or register number camera recognition to enter our weighing facilities. Transfer documents are linked to these ID options."
Digital Integration and Tools	Internal Platforms	DIC5	"Office365, P-Bi, ProjectTOP, Teams, different financial IT tools, Process monitoring IT, WhatsApp,…"
Digital Integration and Tools	Vehicle Terminal Reporting	DIC6	"They can do this via the vehicle terminal from a drop-down menu. Dashboard or equivalent monitoring tool is under development."
Digital Integration and Tools	GPS Tracking	DIC7	"We use GPS tracking on vehicles and bin locations to monitor this aspect. The RFID bins are not an economical option yet. Reading a QR code is an extra work step not worth the time use, need to be more automatic."
Digital Integration and Tools	AI in Daily Tasks	DIC8	"I use the copilot or Gemini or cloud or whatever. But that is also restricted, like that is not either used to its full potential. I think it's used to help in reports and creating summaries and so on."

Digital Integration and Tools	AI for Segregation	DIC9	"If we would really use AI I think that will be an outside like on the field where for example with these. Waste segregations, you know that the robotics that could, you know, separate materials from each other."
Digital Integration and Tools	Bin Sensors	DIC10	"These sensors in the in the bins that tell us how how full the bins are having a pilot on that one and."
Digital Integration and Tools	Route Planning Programs	DIC11	"We use two different programs... TCS... Vingo... they all have GPS opportunities."
Digital Integration and Tools	Real-Time Data Adjustment	DIC12	"We have about 10 pieces of real time data... how full they are, but not really. We really don't have enough real-time data."
Digital Integration and Tools	Vehicle Terminals for Drivers	DIC13	"Drivers able to send data direct to the vehicle terminals... they can send us notes like this is MTB or this is all too full or and."
Data Collection and Usage	Waste Weighing and Logging	DCU1	"All incoming waste is weighed & logged with corresponding relevant data. We have ~30 years of historical data. Last 7 years available in traceable, high quality digital apps for analysis and trending."
Data Collection and Usage	Data Applications	DCU2	"Logistics, collection point placements, tendering etc."
Data Collection and Usage	Digital Tools for Circular Economy	DCU3	"Material flow, knowledge, and analysis are crucial for a successful circular economy. Digital tools are a must in so many different aspects of this."
Data Collection and Usage	Recycling Calculation Tool	DCU4	"We have developed a recycling calculation tool. And are part of a workgroup to develop a national recycling calculation tool."
Data Collection and Usage	Efficiency Studies	DCU5	"We have done efficiency studies on how well certain waste is segregated. and only when we got, when we got all that data into digital format, so you could actually start to play with it."

Data Collection and Usage	Statistical Correlations	DCU6	"We can actually get from the finish official statistics are scaringly good. So I can take bippostage number, I can tell you what is the average level of education within that area... And then when we compare that to the sorting, there's no connection."
Data Collection and Usage	Historical Collection Impact	DCU7	"How long have we been collecting this waste? How long have we been informing about how to collect this specific waste? Turns out that metal, glass, newspapers, and cardboard... Works fine. Everything else less so."
Data Collection and Usage	Data Flow Optimization	DCU8	"By looking at the data flow and that comes again in your questions comes into this when we're looking at the data flow, and we're looking at the material flows, we, for example, saved 40,000 euros in effectivizing our logistics last year."
Data Collection and Usage	Raw Data Messiness	DCU9	"The raw data itself... is quite messy... you have to do a lot of manual work to clean it up."
Data Collection and Usage	Manual Data Cleaning	DCU10	"I use tools like hexadecimal to find the hidden quirks... I generally never trust it when I get it."
Data Collection and Usage	Collection Operations Data	DCU11	"Once a month they form a package which is holds inside all the all the collection operations and there comes the. It it comes money that way that that we owe the company."
Organizational Adaptation and Learning	Training for Segregation	OAL1	"We would give a training in how you segregate and what you're supposed to do, according to the instructions that we have for the most Vasa area."
Organizational Adaptation and Learning	Cultural Differences in Communication	OAL2	"People could talk with people from their own country who would understand the language and the cultural differences... German people, you just tell them, oh, this is how you should do. They would go, yes, sir."

Organizational Adaptation and Learning	Repetition in Education	OAL3	"The mother of all schooling is rep repetition, repetition, repetition, check, repeat, repeat, check, check, repeat. It's no different."
Organizational Adaptation and Learning	Staff Fears of Job Loss	OAL4	"Some fears... they fear that if there comes efficient tools... they lose job."
Organizational Adaptation and Learning	Continuous Learning	OAL5	"Continuous learning. So I think the collaboration here is the main one."
Organizational Adaptation and Learning	Operational Quality Improvement	OAL6	"The quality... when we started 2 1/2 years ago it was terrible... nowadays... quality is quite good."
Organizational Adaptation and Learning	Training Needs	OAL7	"What kind of training is needed to help staff use these tools confidently?"
Technical Subsystem	Vehicle Terminals	TS1	"All vehicles are mandated to have a drive-terminal in the vehicle."
Technical Subsystem	Bin Sensors Pilot	TS2	"We are testing remote bin level sensors for remotecollection points."
Technical Subsystem	QR and RFID Integration	TS3	"Transport companies use QR-codecards, RFID-tags or register number camera recognition to enter our weighing facilities."
Technical Subsystem	Process Monitoring IT	TS4	"Process monitoring IT, WhatsApp…"
Technical Subsystem	AI Robotics for Segregation	TS5	"The robotics that could, you know, separate materials from each other. To to put this waste into different fractions like the clear, like clean up the fractions."
Technical Subsystem	Sensor Challenges	TS6	"While using those kinds of technologies you come up with the challenges with those ones like they the batteries running out or someone is breaking it down."
Technical Subsystem	Route Planning Software	TS7	"We use two different programs to plan those routes and areas... TCS... Vingo."
Technical Subsystem	Real-Time Bin Data	TS8	"Real time data. I don't know it again in English that sends us real time data. How, how, how full they are."

Technical Subsystem	Energy Harvesting Project	TS9	"We are with with was a university. So that's called data harvesting project."
Social Subsystem	Language Barriers with Immigrants	SS1	"80% of the inhabitants were either immigrants or Ukrainian refugees... all the information was only in written Finnish... we put this, you know, like this self adhesive labels... Two weeks, and the whole picture changed."
Social Subsystem	Information Dissemination Issues	SS2	"The information probably hasn't gone out properly. Maybe there is some pamphlet somewhere in that drawer that no one ever sees."
Social Subsystem	Cultural and Educational Differences	SS3	"Some people are really thinking, I mean, if you look at the sweets, they are thinking already much more green than fins, for example, because they have been from the very beginning in school."
Social Subsystem	Immigrant Integration	SS4	"A lot of people who come here as immigrants... tend to actually want to be kind of more friendly and really hard at try to integrate and to be according to the society."
Social Subsystem	Isolated Communities	SS5	"Mostly in w apartment in that areas, people are living is who are the immigrants not any Finnish people person or anyone. So they are like isolated people."
Social Subsystem	Attitude Toward Recycling	SS6	"Attitude maybe? All the people don't want to do this so well, the recycling, how how it's supposed to do."
Joint Optimization (Socio-Technical Alignment)	Socio-Technical Data Use	JOTA1	"When we digitalized it and we could see this analysis and we could see you know, like trends in what is happening... You could adjust your process."
Joint Optimization (Socio-Technical Alignment)	App for Immigrants	JOTA2	"What I'm going to suggest is an app that app is like they are acting as the intermediary party between Stomosin or another ways collecting company and the people who are who need to destroy their weights."

Joint Optimization (Socio-Technical Alignment)	Multilingual App Instructions	JOTA3	"If you open our phone app, there is sorting instructions available in three languages."
Joint Optimization (Socio-Technical Alignment)	Incentive Alignment	JOTA4	"If you don't want to segregate, don't segregate. You just pay four times more."
Joint Optimization (Socio-Technical Alignment)	Digital and Social Reach	JOTA5	"How do we get people to go and look for the information and raise the interest?... How do we reach all the people? How do we know that we have reached them?"
Joint Optimization (Socio-Technical Alignment)	AI Efficiency and Job Impact	JOTA6	"If we would have proper digital data collection... we could make an AI that would pick out the necessary data... cut two people, three weeks down to one person, two days."
Circular Economy Outcomes	Recycling Targets	CEO1	"How do digital tools help you with your recycling, reuse, or sustainability targets? Material flow, knowledge, and analysis are crucial for a successful circular economy."
Circular Economy Outcomes	Impact of AI Projects	CEO2	"Not yet, but there will, or rather must be in the future."
Circular Economy Outcomes	Progress Tracking	CEO3	"We have developed a recycling calculation tool."
Circular Economy Outcomes	Material Reuse	CEO4	"Let's see where can we for example, discuss with the city... you can use it as a neccoertilizer... It's cheap, it's free, it's near."
Circular Economy Outcomes	Logistics Support for Goals	CEO5	"We collect from private persons... fractions of waste separately. So plastic... glass and metal... I hope we are helping this environmental part of this, our company's recycling and certainly economic goals."
Challenges and Opportunities	Segregation Problems	CO1	"The way segregation was basically zero... they had all the bins different for segregation and segregation just didn't happen."

Challenges and Opportunities	Information Accessibility	CO2	"None of your inhabitants in that specific housing complex speak Finnish or read Finnish?"
Challenges and Opportunities	Social Media Reach	CO3	"If we look at how many visits we have on our social media sites... it's like, you know, 600 followers 1,400 visits, nothing, like zero."
Challenges and Opportunities	Practical Logistics Challenges	CO4	"They're quite practical in winter time, snow. Cars that are parked before or in the way to the waste bins that we can't, we can't collect them."
Challenges and Opportunities	Data Quality Challenges	CO5	"The raw data itself... is quite messy... you have to do a lot of manual work to clean it up."
Challenges and Opportunities	Sensor Reliability	CO6	"The batteries running out or someone is breaking it down or you know it it just gets destroyed."
Challenges and Opportunities	No Real-Time Data	CO7	"Unfortunately at the moment we are... not really. We really don't have enough real-time data."
Incentives and Motivation for Sorting	Financial Incentives	IMS1	"There is some sort of incentive, either money wise, or saving wise."
Incentives and Motivation for Sorting	Bin Size and Frequency Adjustment	IMS2	"You can go in on our website and say that my bio waste bin is only half full... Can you please come and empty it every second week... So you cut your cost in a half."
Incentives and Motivation for Sorting	Price Manipulation	IMS3	"We put the emptying of the bio waste bin really cheap, and we raise the price of the mixed bin. Then you would be interested in having the mixed bin emptied as seldom as possible."
Incentives and Motivation for Sorting	Punishment Systems	IMS4	"In Germany... waste inspectors... Dark red, this is a complete mess. Then you will get another fine, but during three months, you will pay double raised handling cost."
Incentives and Motivation for Sorting	Choice-Based Costs	IMS5	"If you don't want to segregate, you can get a same size bin without the separation... your waist coast is four times higher."

Incentives and Motivation for Sorting	Incentive Experiments	IMS6	"We are talking about that, but it's really new, and this is experimentally going on over Finland."
Incentives and Motivation for Sorting	Savings for Better Segregation	IMS7	"If they would segregate better they could save this kind of money... but even though we informed the landlords it doesn't make the one who lives... segregate any better."
Logistics and Route Planning	Route Optimization	LRP1	"Logistics, collection point placements, tendering etc."
Logistics and Route Planning	Collection Role	LRP2	"My job is what what I'm called service manager... Originally I planned all the collection operations that we have nowadays."
Logistics and Route Planning	Contractor Planning	LRP3	"Currently we have planned only areas that the companies that drive those collection cost to us, they they sell, they buy their sell themselves. Plan their daily routes."
Logistics and Route Planning	Transport Companies	LRP4	"We use quite a lot... company names so you can take it there."
Logistics and Route Planning	Service Vehicles	LRP5	"We have only one vehicle at Stormosen... or two, but they they are used as a service cars."
Logistics and Route Planning	Real-Time Adjustments	LRP6	"If there comes. No special collection that can you take that to that is not planned so we can set it to the root daily and in in real time."
Logistics and Route Planning	Route Efficiency	LRP7	"They can also by themselves make it more efficient. By by planning routes daily."
Logistics and Route Planning	Bin Status Reporting	LRP8	"Time to time we we give them work to to collect or or check every bin how full it was and send us a percent percent."
Partnerships and Collaborations	External Partnerships	PC1	"Yes [work with other companies, cities, or universities on digital projects]."
Partnerships and Collaborations	Funding Importance	PC2	"Important in collaboration projects, in company internal less so."
Partnerships and Collaborations	University Collaborations	PC3	"The importance of this kind of partnerships that we're doing collaborating with the technology

			companies. But especially with universities and like was auni or Novia."
Partnerships and Collaborations	Network Building	PC4	"You need to have someone else you need to bring. Someone who has the knowledge, you have to collaborate, you have to think together and and have have your your network."
Partnerships and Collaborations	Data Harvesting Project	PC5	"We are with with was a university. So that's called data harvesting project. We are with with them."
Emerging Suggestions and Future Directions	Step-by-Step Digitalization	ESFD1	"Manual reporting -> digital reporting - > automation in reporting -> AI or similar analysis in reporting…."
Emerging Suggestions and Future Directions	AI Impact	ESFD2	"Not yet, but there will, or rather must be in the future."
Emerging Suggestions and Future Directions	App for Immigrants	ESFD3	"An app that app is like they are acting as the intermediary party... we will give them some amounts and all so they can collect on behalf of the people."
Emerging Suggestions and Future Directions	Advertising Through Offices	ESFD4	"We'll ask from them to do the advertising for us. Like they can tell that there is something which you can earn actually. You don't know the waste is money."
Emerging Suggestions and Future Directions	Waste Inspectors	ESFD5	"There is one of these Bundesstad where they have a waste inspectors... This person has the right to go in anywhere to check any waste bin."
Emerging Suggestions and Future Directions	Predictive AI	ESFD6	"A I could use is to help with different kind of predictive analysis. I think like forecasting flows or optimizing the the logistics."
Emerging Suggestions and Future Directions	Open-Mindedness	ESFD7	"I think the one is just to to maintain like open-minded, but also the importance of this kind of partnerships."
Emerging Suggestions and Future Directions	Future Digital Tools	ESFD8	"There's a company... Waste Book... they have the services that a customer can just rely on the bin is going to be. Collected not before it, it's 80 percentage full."

Emerging Suggestions and Future Directions	Button for Bin Fullness	ESFD9	"Every time a driver takes one bin... He presses 1 button that says OK... also there could be for example percentage beside that same same button that. 60% was, it was 60% full."
Emerging Suggestions and Future Directions	AI Support in Logistics	ESFD10	"When you connect that to a I so I can only imagine how how much help it would give us."