EXPLORING THE USE OF DIGITAL TWINS FOR ESG REPORTING UNDER THE ESRS FRAMEWORK

Lappeenranta–Lahti University of Technology LUT

Industrial Engineering and Management, Bachelor's thesis

2025

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Examiner: D.Sc. Tech., Tero Rantala

ABSTRACT

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Sustainability reporting has become significantly more important for organizations in the last few years with new regulations such as the Corporate Sustainability Reporting Directive (CSRD) in European Union. New reporting requirements can be challenging for companies to comply, with emerging technologies companies can navigate these disclosures by improving reporting. This thesis explores the use of digital twins for Environmental, Social, and Governance (ESG) reporting by analyzing reporting requirements, published reports and current literature. The potential of digital twins as a reporting platform was evaluated and the applicability to comply with European Sustainability Reporting Standards (ESRS) was found in environmental reporting, partly in social reporting, but not in governance reporting. In addition, benefits and challenges to implement digital twins for ESG reporting were recognized. Benefits included increased quality, accuracy, and real-time capability. Whereas challenges were concerned with data, cybersecurity, and state of the digital twin development.

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Tuotantotalous

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Digitaalisten kaksosten soveltaminen ESRS standardien mukaiseen ESG raportointiin

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Kestävyysraportoinnista on tullut huomattavasti tärkeämpää organisaatioille viime vuosina uusien säädösten, kuten Euroopan unionin yritysten kestävyysraportointidirektiivin (CSRD) myötä. Uusien raportointivaatimusten noudattaminen voi olla yrityksille haastavaa, kuitenkin uusien teknologioiden avulla yritykset voivat selviytyä näistä raportointivelvollisuuksista helpottamalla raportointia. Tämä kandidaatintyö selvittää digitaalisten kaksosten käyttömahdollisuuksia ympäristö-, yhteiskunta- ja hallintoraportoinnissa (ESG) analysoimalla raportointivaatimuksia, julkaistuja raportteja ja olemassa olevaa kirjallisuutta. Digitaalisten kaksosten potentiaalia raportointialustana arvioitiin ja soveltuvuus Euroopan kestävyysraportointistandardien (ESRS) noudattamiseen havaittiin ympäristö-, osittain yhteiskunta-, mutta ei hallintoraportoinnissa. Lisäksi tunnistettiin hyötyjä sekä haasteita digitaalisten kaksosten käyttöönotossa ESG-raportointiin. Hyötyihin lukeutuivat parantunut laatu, tarkkuus ja reaaliaikaisuus. Haasteet puolestaan liittyivät dataan, kyberturvallisuuteen ja digitaalisten kaksosten kehityksen tilaan.

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LIST OF ABBREVIATIONS

CSRD	Corporate Sustainability Reporting Directive
DT	Digital Twin
EU	European Union
ESG	Environmental, Social, Governance
ESRS	European Sustainability Reporting Standard
	ESRS E European Sustainability Reporting Standard Environmental
	ESRS S European Sustainability Reporting Standard Social
	ESRS G European Sustainability Reporting Standard Governance
IoT	Internet of things
IRO	Impact, Risk, Opportunity
LIDAR	Light detection and ranging

Table of contents

LIST OF TABLES AND FIGURES

Figures

Tables

1 Introduction

Sustainability reporting has become more and more important for organizations in the last few years with new regulations and rising expectations from stakeholders. In 2022, European Union published the Corporate Sustainability Reporting Directive (CSRD) which became applicable in 2024 for large, listed companies (European Union, 2022). It requires the companies to report about their environmental, social and governance activities referred to as ESG – environmental, social and governance reporting dimensions (European Union, 2023). The directive will extend to unlisted large companies and listed small and medium companies in stages until 2028 (European Union, 2022). The number of affected companies is around 50 000 (Dovolil and Svitek, 2024), the consequences to the industries are significant. New reporting requirements can be challenging for companies to comply, with emerging technologies companies can navigate these disclosures by improving reporting and increasing quality (Dudek and Kulej-Dudek, 2024).

Even though companies have been increasing the amount of ESG reporting due to reporting mandates there has not been an increase in the quality of the reports (Arvidsson and Dumay, 2022). Reporting with traditional data collection methods often require extensive manual work which can lead to inconsistencies decreasing quality (Dudek and Kulej-Dudek, 2024). In addition, companies often still report on their sustainability initiatives rather than actual performance (Arvidsson and Dumay, 2022).

Digital twins collect data from objects and systems combining external data to create an identical virtual copy of the physical entity. The virtual counterpart enables automated data analytics, predictive analysis and performance measurement of the ongoing processes in real-time. (Tao et al., 2019) Therefore, there is potential to digital twin technology to being leveraged as a multi-functional platform for sustainability data (Dovolil and Svitek, 2024) solving problems related to ESG reporting.

This work aims to give insight into the potential use of digital twins for ESG reporting by analyzing ESG reporting requirements, published reports and current literature on digital twins. Published company reports are reviewed to identify common metrics for ESG reporting that comply with the CSRD. Based on disclosure requirements and reported

metrics the potential of digital twins as a reporting platform is evaluated. The work aims to find answers to the following research questions:

1. How can digital twin (DT) technology be leveraged for ESG (Environmental, Social, and Governance) reporting, and what specific ESG-related data can be captured, analyzed, and communicated through digital twin applications?
2. What are the current ESG reporting requirements in the European Union, and to what extent can digital twin applications support compliance with these regulatory and industry standards?

The work contributes developing an understanding to using digital twins for ESG reporting under ESRS which can be a starting point for research withing the research area and overview into the benefits and challenges for companies to implement digital twins or expand their use purposes. The work begins with a literature review of the topic, later the methods are described, going into the findings of the company reports and analysis of how digital twins could be used to generate ESG reports. In addition, a conclusion is given to draw a picture into the current state of using digital twins for ESG reporting purposes.

2 Literature review

The following section aims to build a theoretical background in the topic of digital twins in ESG reporting. The section will introduce the key concepts and definitions to understand the findings of the study. The literature review is descriptive review of the current literature analyzing the main themes within the topic to build a strong foundation for future studies in a relatively new research area of applying digital twins for ESG reporting.

Even though later the ESG reporting under ESRS is analyzed within the scope of Finnish listed large companies the literature will include studies beyond Finland due to very limited to non-existent study and applications of DTs for ESG reporting. Structure of the literature review begins with a review of ESG reporting principles and description of DT technology. Further going into describing how digital twins have been applied in the literature for sustainability and ESG reporting in the scope of ESG aspects. Further different DT technologies will be introduced in the scope of the ESRS disclosure requirements.

Scopus was used as the main search engine for finding papers related to the topic of the work. The following keywords and their combinations were used to identify relevant research articles applying Boolean operators. Key words such as “Digital twin”, “ESG”, “Sustainability”, “Reporting”, “Environmental”, “Social” and “Governance”. Papers were evaluated based on the applicability to contribute the defined research questions. Many papers consisted of information related to using digital twins as a management system for sustainability versus being used of reporting. Therefore, the papers results were used if applicable in supporting the ESG reporting processes. The papers were not excluded based on other criteria such as continents to find all relevant studies due to the topic being very new.

To this date digital twins have been mainly studied to be applied for managing sustainability they are often discussed in scope of ESG aspects. Applications and conceptualizations in the area have emerged in smart cities, supply chains, manufacturing, mining, construction and building management. The papers used in this work consisted of literature reviews, frameworks, conceptual and empirical papers.

2.1 ESG reporting

ESG reporting is a framework for companies to disclose information on sustainability from the environmental, social and governance aspects. The environmental aspect refers to reporting the company's actions and impact on the surrounding environment and climate. The social aspect refers to reporting the company's actions and impacts on its stakeholders with whom they have relationships, such as their employees or local communities. Finally, governance refers to reporting about the decision maker, processes and transparent business conduct. (Oliver, 2024) The European Union is now adapting ESG reporting with CSRD and making ESG reporting mandatory (European Union, 2022).

The CSRD requires companies to report according to the European Sustainability Reporting Standards (ESRS). The ESRS defines the scope of the ESG reporting for companies in the EU and requires disclosing information on their ESG activities as an integrated component of their annual financial reporting. The ESRS consists of 12 standards (Table 1.) from which ESRS 1 and ESRS 2 define the general disclosure standards for the reporting. The reporting framework requires the companies to report each standard from specific aspects, and in some cases, defines the metrics used in each reporting dimension. (European Union, 2023).

Table 1. ESRS reporting standards (Adapted from European Union, 2023)

Number	**Subject**
Cross-cutting	
ESRS 1	General requirements
ESRS 2	General disclosures
Environmental	
ESRS E1	Climate change mitigation and adaptation
ESRS E2	Pollution
ESRS E3	Water and marine sources
ESRS E4	Biodiversity and ecosystems
ESRS E5	Resource use and circular economy
Social	
ESRS S1	Own work force
ESRS S2	Workers in the supply chain
ESRS S3	Affected communities
ESRS S4	Consumers and end-users

Governance	
ESRS G1	Business conduct

ESRS requires companies to state their strategies and conduct an impact, risk and opportunity analysis (IRO) and metrics and targets in each reporting category. Under these 12 reporting standards (Table 1.), there are multiple subtopics. The subtopics consist of requirements for companies to analyse materiality, transition plans, policies, action plans, targets, potential financial effects, quantitative metrics, and qualitative disclosures within the scope of the standard. (European Union, 2023). In 2026, the EU will publish 41 sector-specific standards (Council of the European Union, 2024). However, there are some political uncertainties about whether this will go forward.

Before CSRD, ESG reporting was a voluntary disclosure for companies in the EU, and the issue in reporting has been the lack of quality and trust (Serag and Musleh Al-Sartawi, 2021). The reports have been accused of greenwashing, where the company's claims do not match the reality of the sustainability actions and impacts (Asif, Searcy and Castka, 2023). CRDR in the EU tries to combat these problems with a unified reporting framework.

Reporting the ESG metrics requires establishing processes for data collection, processing and analysis. The quality and reliability of the data are one of the most significant issues in ESG reporting. As the CSRD requires companies to audit the reported information, those issues become even more pressing (Krasikov and Legner, 2023). Auditing of the reports will become mandatory under the CSRD in 2028 (European Union, 2022). Audits of ESG reports require the companies to report data that external auditors can trace (European Union, 2022). The reported information must be traceable and authentic for the auditing process to succeed.

2.2 Digital twin

Digital twin has developed from a conceptual model in product lifecycle management to a significant technology across industries. Initially introduced in early 2000s, the DT was seen as a part of PLM, where a physical object is connected and in synch with the digital counterpart. (Tao et al., 2019) DT has often been addressed in the manufacturing context although it has many other use cases and potential (Singh et al., 2021).

Now, digital twins are seen as a virtual representation of a physical object, process or system continuously updated with data to represent the performance of the physical counterpart. DT system's special feature is its bidirectional data flow, where the physical counterpart updates the virtual one with data from current processes, and the virtual counterpart adjusts based on the data, which can be carried out in the physical system. Therefore, the virtual counterpart stores the full operational history of the physical part. (Tao et al., 2019)

Digital twins can have many capabilities for analysis and management purposes. Real-time simulations, estimations on future performance, data analytics, and malfunction detection, which are performed in the virtual counterpart of the DT, can be used for optimisation of processes and operations (Alnaser, Maxi, and Elmousalami, 2024). Simulations enable performance analysis under different conditions to gain predictive insight (Tao et al., 2019). Expanding DT capabilities even more, there can be integrated IoT sensors, virtual reality, artificial intelligence, blockchain and cloud computing features (Kamble et al., 2022). In addition, DTs can be supplied with data from other management systems (Traini et al., 2024).

Digital twins not only cover one object or equipment but can cover entire processes at a factory or enterprise level (Böttjer et al., 2023). This allows for the data to be collected from all parts of the operations. DTs generate huge amounts of data, which can be utilized by applying analytical algorithms and models (Eswaran et al., 2025). Yan, Hong and Warren (2022) propose that DT systems can integrate all existing reporting frameworks, such as key performance indicator (KPI) systems for performance management, due to the ability to communicate data. To perform accurate data analysis, there needs to be an automated data collection process that filters the data for accurate reporting, and the ability to merge data from multiple sources and data types (Eswaran et al., 2025; Suhail et al., 2022).

2.3 Digital twin in ESG data generation and collection

DT systems collect data from multiple sources that can be further analyzed and utilized for ESG reporting. Digital twins make sustainability data usable for reporting purposes (Trienens et al., 2024). The granular data collection enables more informative and better insights due to the high level of specific measurements. DT facilitate the data and provides a retrospective look into the operations due to storing the full operational history (Trienens

et al., 2024). Combined with blockchain technologies, it enhances the traceability of the data and enables auditing of the collection process and results (Suhail et al., 2022). Retrospectivity enables auditing processes and increases the authenticity of reports (Asif, Searcy and Castka, 2023; Trienens et al., 2024). The automated data collection and analysis process improves the efficacy and reduces costs due to the processing capabilities that are not otherwise manually reached (Asif, Searcy and Castka, 2023). Benefits of DTs are rooted in the ability to collect data from multiple sources and to combine historical and real-time data for more accurate analysis. The accuracy is enabled by providing data from the ongoing operations context from external sources. (Wagstyl et al., 2024)

2.3.1 Environmental data

Different environmental data can be collected using digital twins such as use of resources, emissions and energy-related metrics. Manufacturing facility's water systems can be modelled and monitored in real time to track water usage, waste waters, concentrations of harmful substances in the water (Omrany, Mehdipour and Oteng, 2024). Impact of water and marine resources could be even further analysed as Duarte et al. (2024) propose that DT can analyse marine pollution, in addition to analysing the impact of climate change mitigation and human interventions. This contributes not only to marine resources analysis but to measuring the impact on marine biodiversity and ecosystems.

Carbon emissions can be measured holistically with sensors that collect data in a DT from the manufacturing processes and combining the data from the machinery or process's energy consumption with energy inputs from different energy sources (Metallidou et al., 2022). Other emissions to air such as nitrogen dioxide and methane can be measured with different sensors connected to the digital twins (Aly, Hustim and Zakaria, 2019; An and Chen, 2021).

In waste management DTs can be used to collect data on total waste outputs and inputs, composition of the waste, and recovered materials (Giel and Dąbrowska, 2024). Further resource use can be tracked in the context of circular economy and reuse of resources (Mügge et al., 2024). Resource management can be done at multiple levels: material, component and machine level. In addition, Yelda et al. (2024) suggest that digital twins are capable in tracking materials and carbon emissions that are caused by replacements during the object life cycle.

Impact on biodiversity and ecosystems of the company's surrounding areas can be monitored with digital twins and utilizing simulations (Sun and Xu, 2024). Especially changes in the environment can be followed to gain information of the development in the surrounding ecosystems with DT's using LIDAR technology and drones (Cranford, 2023; Schrotter and Hürzeler, 2020). Sun and Xu (2024) also found that monitoring ecosystems in real-time would lead to more efficient environmental protection. Risks and impact of environmental factors affecting the business operations can be assessed with DTs using historical and topographical data for environmental analysis (Mishra, Kumar and El Barachi, 2024).

2.3.2 Social data

Safety and wellbeing of the employees can be observed in the work environments in multiple ways such as recording data on exposure to hazardous environments or potential safety violations (Omrany, Mehdipour and Oteng, 2024). Factors affecting the work environment such as noise emissions (Omrany, Mehdipour and Oteng, 2024), indoor air quality (Qian et al., 2024), humidity and temperature (Shah et al., 2024) can be measured. Shah et al. (2024) found that by using DTs for waste management systems exposure of employees to hazardous waste could be identified. These emissions do not only affect the own workforce of the companies but the local communities. Therefore, digital twins can be also used to assess the impact on affected communities and ecosystems. End-user impact using cyber physical products can be assessed by the manufacturing company. Digital twins can be also used as learning environments for training employees and to track their skill levels in ongoing work operations (Cranford, 2023; Omrany, Mehdipour and Oteng, 2024).

2.3.3 Governance data

Currently there is a lack of studies that present applications or metrics with digital twins for governance reporting. Although digital twins can be used as a tool for governance purposes, for decision making processes visualizing and providing data (Cranford, 2023). Previously mentioned, DTs improve transparency and traceability of reporting and decision making. Transparent data can be used to support policy and regulation decisions. Data can be used to facilitate sustainable decision-making processes and to generate sustainability KPIs

(Trienens et al., 2024). Collecting data with DTs results unbiased data collection opposed to using surveys and processing ESG data manually. DTs do not only facilitate training for the employees, but it enables participation in the development activities such as identification of challenges and solutions (Korepin et al., 2024). DT provides the data in an understandable format (Wagstyl et al., 2024)

3 Methodology

This chapter describes the methods used to find data for the empirical study on sustainability reports published under the CSRD. The companies were selected based on the current state of adoption of the CSRD at the time of writing this thesis work. The first companies to adopt the reporting were large, listed companies with over 500 employees. These companies needed to start reporting in 2025, covering the 2024 fiscal year under the CSRD. The companies selected were listed in Finland and operated in different manufacturing industries. Digital twins are most extensively applied in manufacturing companies (Tao et al. 2019); therefore, the suggested reporting method would be the most feasible.

The companies are described in Table 2. All the companies were categorized in high climate impact sectors, which will have to report more in detail in some categories, such as in the ESRS E1 – climate change and mitigation (European Union, 2023). Data was collected from companies' public annual reports published on the company websites. The results were further processed to find the reporting metrics used under ESRS and then compared to the results of the literature review to determine whether digital twins could be applied for the reporting of the aspect. From the ESRS reporting standards only IRO analysis, metrics and targets were included in the work to examine the applicability of digital twins. The specific aspect can be seen in Tables 3-5.

Table 2. Description of the analyzed companies

Indicator	**Industry**
Company 1	Chemistry
Company 2	Forestry
Company 3	Metal industry
Company 4	Packaging solutions
Company 5	Manufacturing

4 Findings

The following section examines public ESG reports to find current industry standards and metrics for measuring sustainability in the scope of environmental, social and governance standards. The cross-cutting standards ESRS 1-2 were excluded from this analysis as they apply to the overall reporting quality and disclosure requirements. Additionally, the sustainability programs and guidelines reported under the ESRS were not considered in the findings due to the concentration of this work being in reporting metrics and IRO analysis. The aim is to find out what metrics are being used in the reports to evaluate the applicability of DTs based on the literature review results.

The companies collected sustainability data through estimations, calculations, and direct measurements. Estimations were used in conducting the analysis of the actions in the supply chain, for example, in Company 2's case, there were insufficient data provided by the parties in the supply chain. Lack of data and knowledge on the impact and relevance were stated as the reasons for not disclosing all the required information in the reports. The transition provision under ESRS 1 allows companies to delay reporting up to one year for information on the value chain, anticipated financial effects, and environmental information not including ESRS E1 – climate change mitigation and adaptation (European Union, 2022).

The findings are presented in the form of a table which lists all the specific reporting requirements within ESRS E1-5, ESRS S1-4, and ESRS G1. The results in the tables combine the literature review and analysis of industry reports. "DT generated" indicates the potential to fulfil the reporting requirements, and "External systems" suggests the need to use other reporting systems to disclose the information. Some results might indicate that both digital twin-generated and external systems can provide the metrics. The tables presented are generalizations to give direction on the potential of using digital twins based on the authors interpretations.

4.1 Application to ESRS E1-5

ESRS E1 – Climate change mitigation and adaptation was measured by the companies according to the ESRS E1-4 targets related to climate change and mitigation, E1-5 Energy

consumption and mix, E1-6 Gross scopes 1-3 and total GHD emissions, E1-7 GHG removals and GHG mitigation projects financed through carbon credits in the reports (European Union, 2023). The companies included reporting different metrics related to sources of energy, shares of consumption and sources of emissions, which DTs can measure and analyse. E1-8 Internal carbon prizing was included by company 3, although it was stated as an internal metric. For internal carbon prizing digital twins could be used to develop an understanding of the scope of impact of investments.

ESRS E2 – Pollution metrics are defined in the ESRS to be reported in the scope of E2-3 targets related to pollution, E2-3 pollution to air, water and soil, E2-4 substances of concern and high concern (European Union, 2023). Not all companies disclosed these requirements. Companies 4 and 5 had left the pollution reporting out of their report. Companies 1-3 had reported their pollution metrics in emissions to air, water, and soil and listed the amounts of substances of concern used in their operations. Additionally, company 2 reported incidents related to emissions to water and air that were non-compliant. DTs can support measuring the related incidents and the amounts of pollutants through resource management, following emission rates and exposures to hazardous substances.

ESRS E3 – Water and marine resources require reporting through E3-3 targets related to water and E3-4 water consumption (European Union, 2023). Company 5 did not disclose any information related to water and marine resources. Water consumption, intensity, and recycling rate were reported by companies 1- 4. Water withdrawals and discharges were reported by companies 2, 3 and 4. In addition, companies had reported their water consumption in high-risk areas, water consumption per segment, water storage and withdrawals and discharges by sources. DT support the water and marine reporting; in addition, it can support the impact analysis of water and marine resources.

ESRS E4 – Biodiversity and ecosystems are measured through E4-4 targets related to biodiversity and ecosystems, E4-5 impact metrics related to biodiversity and ecosystem change (European Union, 2023). Companies 1 and 5 did not disclose any metrics related to this area. Companies 2, 3 and 4 had listed their sites located near biodiversity-sensitive areas. Company 4 had disclosed information on the sources of material from recycled or eco-friendly certified sources. Company 2 was the only company with more extensive biodiversity and ecosystems disclosure as a forestry company. They measured the compliance rate of biodiversity impact indicators, certificate coverage, non-compliance

events, sources of wood materials, estimated annual forest growth, annual harvesting and total standing stock of the forests. The compliance rate of biodiversity impact indicators included metrics such as high stump creation, ground deadwood preservation, soil and water protection, prioritized habitat preservation, tree retention and buffer zone preservation. DT support biodiversity and ecosystem assessment. For example, sites located near biodiversity-sensitive areas change and the DT can monitor the changes in the environment.

The last environmental reporting standard ESRS E5 – Resource use and circular economy consists of E5-3 targets related to resources and circular economy, E5-4 resource inflows and E5-5 resource outflows (European Union, 2023). The companies reported resource inflows by measuring the amounts of materials used in the operations and the shares of materials from reused or recycled materials. All the companies reported outflow of resources by reporting on the amount of hazardous, non-hazardous waste, the total amount of waste generated and the amount of non-recycled waste. Company 1 additionally reported metrics related to recycling of waste, the amount of waste in preparation for reuse, and the share of other recovery operations used. Whereas company 2 reported on the rate of recyclable content in their products.

Each environmental reporting standard includes metrics related to the anticipated financial effects of each area (European Union, 2023). DTs can support reporting the E1-9, E2-9, E3-5, E4-6, E5-6 through analysis of environmental scenarios by simulations, modelling and predictive analysis. This also applies to the IRO analysis for environmental standards. Further, the results are presented in the Table 3, which indicates the applicability of digital twins in the environmental reporting area.

Table 3. Applicability of DT for environmental metrics (Adapted from European Union, 2023; Author´s interpretations)

ESRS standard	**Description**	**DT generated**	**External systems**
ESRS E1 – Climate change mitigation and adaptation			
Disclosure Requirement E1-4	Targets related to climate change mitigation and adaptation	X	
Disclosure Requirement E1-5	Energy consumption and mix	X	

Disclosure Requirements E1-6	Gross Scopes 1, 2, 3 and Total GHG emissions	X	
Disclosure Requirement E1-7	GHG removals and GHG mitigation projects financed through carbon credits	X	
Disclosure Requirement E1-8	Internal carbon pricing	X	X
Disclosure Requirement E1-9	Anticipated financial effects from material physical and transition risks and potential climate-related opportunities	X	X
ESRS E2 – Pollution			
Disclosure Requirement E2-3	Targets related to pollution	X	
Disclosure Requirement E2-4	Pollution of air, water and soil	X	
Disclosure Requirement E2-5	Substances of concern and substances of very high concern	X	
Disclosure Requirement E2-6	Anticipated financial effects from pollution-related, risks and opportunities	X	X
ESRS E3 – Water and marine resources			
Disclosure Requirement E3-3	Targets related to water and marine resources	X	X
Disclosure Requirement E3-4	Water consumption	X	
Disclosure Requirement E3-5	Anticipated financial effects from water and marine resources-related impacts, risks and opportunities	X	X
ESRS E4 –Biodiversity and ecosystems			
Disclosure Requirement E4-4	Targets related to biodiversity and ecosystems	X	X
Disclosure Requirement E4-5	Impact metrics related to biodiversity and ecosystems change	X	
Disclosure Requirement E4-6	Anticipated financial effects from biodiversity and ecosystem-related risks and opportunities	X	X
ESRS E5 –Resource use and circular economy			

Disclosure Requirement E5-3	Targets related to resource use and circular economy	X	X
Disclosure Requirement E5-4	Resource inflows	X	
Disclosure Requirement E5-5	Resource outflows	X	
Disclosure Requirement E5-6	Anticipated financial effects from resource use and circular economy-related impacts, risks and opportunities	X	X

4.2 Application to ESRS S1-4

As required the social information on the ESG reports all began with the IRO analysis in each category ESRS S1-4. For the IRO analysis, simulations could be used in the DT to recognize risks associated with ESRS S1 own workforce and further work conditions. All the companies had stated in the analysis that the health and safety of the workers was a risk. This analysis could be supported with simulations of the work environment to detect different safety concerns, risks and exposure to potential safety hazards. Other analysis was related to for example secure employment, harassment, diversity and training which are not DT supported metrics.

All the companies had reported incidents related to ESRS S1 – own workforce, and company 4 specifically lost time due to incidents. These could be generated with DT due to its ability to follow the manufacturing machineries' emergency data, such as the use of emergency stop functions. Other social metrics within the ESRS S1 are mainly related to diversity, employee turnover, contract types and paying employees. Only company 2 had disclosed metrics for ESRS S2 – workers in the value chain, other did not yet have quantifiable metrics in the area. Company 2 had measured the coverage of their code of conduct policy within their suppliers in the value chain, which enforces sustainable sourcing. In this area of social reporting metrics, DT are less likely to contribute directly as a measurement tool for reporting. Although when supplied with external data from other management systems, the reporting metrics can be collectively generated in the digital twin to produce a cohesive report.

ESRS S3-4 was not disclosed by all the companies due to lack of data. Company 2 had analyzed their impact on use of land and water and sanitation resources in the scope of affected communities complying with ESRS S3. DT could be part of the assessment and further in generating measurements on the impact on land and water resources. For ESRS S4 – end-users, company 4 had reported their product related incidents, and company 5 followed the metric internally without disclosing it in the report. With company 4, DTs are not applicable as the product is related to packaging materials. Whereas for company 5, they could follow their incident rate in addition to claimed reports by creating a DT for the manufactured machines to follow use in the scope end-users for reporting purposes. This data can then be further brought into the ESG digital twin to include in the reports from external systems.

Digital twins partly support the ESG reporting in the scope of social reporting the applicability compared to the ESRS metrics and targets is presented in the table 4.

Table 4. Applicability of DT for social metrics (Adapted from European Union, 2023; Author´s interpretations)

ESRS standard	**Description**	**DT generated**	**External systems**
ESRS S1 – Own workforce			
Disclosure Requirement S1-5	Targets related to managing material negative impacts, advancing positive impacts, and managing material risks and opportunities	X	X
Disclosure Requirement S1-6	Characteristics of the undertaking's employees		X
Disclosure Requirement S1-7	Characteristics of non-employee workers in the undertaking's own workforce		X
Disclosure Requirement S1-8	Collective bargaining coverage and social dialogue	X	X
Disclosure Requirement S1-9	Diversity metrics		X
Disclosure Requirement S1-10	Adequate wages		X

Disclosure Requirement S1-11	Social protection		X
Disclosure Requirement S1-12	Persons with disabilities		X
Disclosure Requirement S1-13	Training and skills development metrics	X	X
Disclosure Requirement S1-14	Health and safety metrics	X	X
Disclosure Requirement S1-15	Work-life balance metrics		X
Disclosure Requirement S1-16	Compensation metrics (pay gap and total compensation)		X
Disclosure Requirement S1-17	Incidents, complaints and severe human rights impacts	X	X
ESRS S2 – Workers in the value chain			
Disclosure Requirement S2-5	Targets related to managing material negative impacts, advancing positive impacts, and managing material risks and opportunities	X	X
ESRS S3 – Affected communities			
Disclosure Requirement S3-5	Targets related to managing material negative impacts, advancing positive impacts, and managing material risks and opportunities	X	X
ESRS S4 Consumers and end-users			
Disclosure Requirement S4-5	Targets related to managing material negative impacts, advancing positive impacts, and managing material risks and opportunities	X	X

4.3 Application to ESRS G1

All the companies had their IRO analysis of the governance practices, in addition to listing their policies for business conduct. Utilizing DTs for the IRO analysis could be less likely

for the governance reporting, as the analysis does not necessarily require, for example simulations or modelling to be done. Metrics related to governance disclosures found in the company reports were measuring mostly ESRS G1- corruption and bribery. Company 1 had measured their coverage of anti-corruption training for white-collar employees by region in terms of number of employees and percentual coverage. Additionally, company 2 had further disclosed the time used for training, the delivery method, and the frequency. Company 4 had instead further reported their training coverage for each area of training. This data can be generated in the ESG DT from DTs used for training purposes or by supplying external data to the reporting system. Similarly, external data could be collected to report incidents of corruption or bribery, which were disclosed numerically by company 1 and company 5 as filed reports and initiated investigations. Although the DT training environment can supply the time used for the training and the type of training.

Table 5 presents the analysis for applying digital twins for ESRS G1 from the metrics and targets perspective. Expanding the reporting scope and aligning with the company metrics DTs could provide data on the training of the employees in the governance aspect. In governance reporting, DT does not present similar opportunities as for environmental and social dimensions due to the digital twin technology collecting data from cyber physical entities, which does not cover policies and decision-making processes.

Table 5. Applicability of DT for governance metrics (Adapted from European Union, 2023; Author´s interpretations)

ESRS standard	**Description**	**DT generated**	**External systems**
ESRS G1 – Business conduct			
Disclosure Requirement G1-4	Confirmed incidents of corruption or bribery		X
Disclosure Requirement G1-5	Political influence and lobbying activities		X
Disclosure Requirement G1-6	Payment practices		X

5 Discussion and analysis

This section discusses the results from the literature review, the findings of the industry reports, and potential related to digital twins in ESG reporting. In addition to the discussion of challenges to ESG Digital Twin implementation. First, results of the study are discussed, and the ESG DT is presented. Finally ending with the discussion of challenges on the DT implementation, as it is a significant question for evaluating the potential of digital twins' application for ESG reporting.

DT does not just provide a platform for reporting but for managing sustainability and a tool for reaching goals related to ESG. Digital twins' systems collect large amounts of data, which can be utilized further for reporting purposes. The findings in Tables 3-5 show the DT potential in generating the ESG related data in the scope of ESRS based on the results found in the literature review of DT applications. The largest potential is in environmental reporting, partly in social reporting. Governance reporting is not supported with digital twins in the current reporting scope. Although companies that consider reporting on their decision-making processes can utilize DT to engage employees and local communities and thereby collect information about the participation in decision making. For DT to act as a comprehensive system for ESG reporting, it needs to be supplied with data from other management systems, especially related to social and governance aspects.

5.1 Benefits of digital twins for ESG reporting

Digital twins provide more reliable and accurate data. DTs support better governance practices but applying them for governance reporting under ESRS is unlikely due to the DT's operational scope. This was also seen from the literature review, there is still very little research about what digital twins could provide to governance reporting. Although the reliability of reports is better compared to relying on employees own reports, which could be considered an aspect of governance,. For example, digital twins can monitor malfunctions and safety hazards in real-time compared to reports made by the affected employees themselves. Therefore, the reporting is not reliant on the willingness to report, and reports present the reality of the operations accurately.

Significant benefits of DTs are the ability to generate reports in real-time and instantaneously (Asif, Searcy and Castka, 2023). The real-time feature of DTs can support the reporting processes and make the reports more accurate. For example, company 5 stated that their reports had to rely on estimates for the last quarter of 2024 due to not receiving supplier invoicing on time for the reporting. Whereas if DTs are implemented in the supply chain, accurate data could be generated in real-time to fulfil the needs of the parties along the supply chain in a timely manner. For example, utilizing blockchain technologies to track material flows, consumption data can be followed in real-time rather than relying on invoicing.

The companies that were chosen for the work took the freedom to postpone the reporting of the anticipated financial impact of the ESG issues from 2024 reports. There weren't given reasons specifically for leaving it out of the reports. In general, the companies stated that parts of the reporting were left out due to the lack of knowledge and undefined metrics. Korepin et al. (2024) state that DTs can be used to support financial forecasting by utilizing simulations to analyze different scenarios and their impact. Even though this work's main concentration is on metrics and targets, it was recognized that digital twins can help in the process of forming ESG strategies for companies as simulations enable analysis of different scenarios. Simulations could play an important role in ESG reporting as they can help define for example, greenhouse gas (GHG) emission metrics (Asif, Searcy and Castka, 2023).

5.2 ESG digital twin

For future development, consideration of digital twins' potential for acting as complete reporting systems is required. Figure 1 presents the process of how the ESRS and industry standards provide the reporting framework for the ESG digital twin, which covers the whole enterprises operations and is supplied with external data resources.

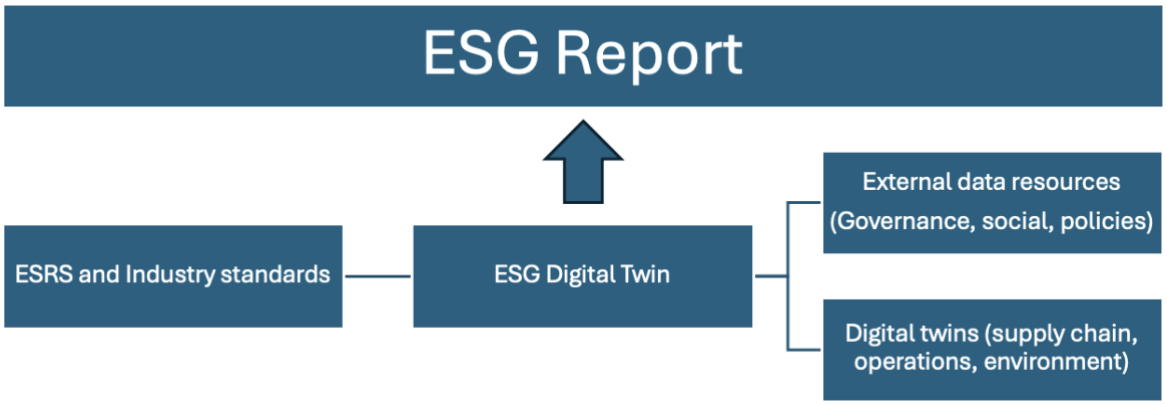

Figure 1. ESG report generation process with digital twin

Even though this work shows that digital twins can support in ESG reporting and specifically fulfilling ESRS disclosure requirements. Still digital twins are not able to generate data on all the reporting areas such as social and governance aspects. As an example, data on employee diversity or cases of misconduct would need to be brought to the DT system from external management systems for completed reporting.

The tables 3-5 show the areas where external data must be brought into the DT system. Therefore, digital twins are insufficient for ESG reporting and providing data for ESRS requirements as a standalone reporting system. It also needs to be considered whether digital twins would be more likely to be used as a reporting platform with external data or part of a reporting process or system. Additionally, it needs to be evaluated if it is beneficial to implement DT for all areas of reporting or to use potential existing systems. As part of a reporting process and system, companies can implement digital twins in areas where their implementation is more critical, creating more value. Then, rely on other reporting methods elsewhere.

5.3 Challenges in the implementation of digital twins for ESG reporting purposes

There are challenges that restrict the companies from using digital twins, such as trade-offs, costs and data concerns. Even though digital twins present a great platform for ESG reporting and managing sustainability, which helps in complying with legal requirements (Trienens et al., 2024). Companies need to consider the sustainability trade-offs, such as increased energy consumption in operating and managing DTs and the associated data (Trienens et al., 2024; Suhail et al., 2022). Although digital twins have been shown to reduce energy consumption

and increase the efficiency of the systems, companies need to evaluate the savings and costs of digital twins. Implementing digital twins requires significant investments and integration to existing systems, so it might be less likely to be used for ESG reporting due to the high costs of the systems (Zhang et al., 2023). Similarly, there are significant development costs associated with the integration of digital twins (Trienens et al., 2024).

Issues with interoperability with existing systems might be faced. Therefore, it must be evaluated whether it is worth changing already existing systems. Integration issues with the DT reporting platform further extend to how to integrate external partners in the supply chain to achieve a comprehensive digital twin (Kamble et al., 2022). Trienens et al. (2024) state that there is a need for standardized guidelines and comprehensive frameworks for the development and integration of digital twins.

For the successful integration of digital twins, it is required that challenges regarding data are managed. Digital twins store large amounts of sensitive company data. Therefore, cybersecurity issues must be accounted for in the systems (Kamble et al., 2022; Trienens et al., 2024). Privacy is critical in ESG reporting as data related to social aspects can contain employee's personal information. Cybersecurity is not the only challenge related to data, as there are also challenges of data quality and management to be considered. Data quality can significantly affect the digital twin's functions, leading to inaccurate simulations and analysis (Kamble et al., 2022). The generated data is in large volumes, therefore the challenge of storage of the data needs to be addressed (Suhail et al., 2022). In addition, for DT to be applicable for ESG reporting, it needs to meet the quality standards for data management in the reporting and align with ISO certificates and industry standards (Dovolil and Svitek, 2024). This requires the developers in the industry to follow the development of the data quality standards to implement them in DT systems.

Zang et al. (2023) argue that when stakeholders like the public see more benefits in ESG reporting, investing in digital twin technology increases, and companies are more likely to invest in the technology if there are penalties for the lack of ESG reporting (Zang et al., 2023). In addition, the implementation of digital twins for ESG reporting requires commitment from the stakeholders within the company. Investing in large DT systems for all areas of ESG reporting alone might not be favorable for companies.

This work recognized multiple applications of digital twins for measuring different aspects of ESG. For digital twins to become an established system for ESG reporting, there must be comprehensive applications and expertise in the industry about digital twins (Cranford, 2023). For example, Canford (2023) recognizes that for the mining industry to adopt digital twins, solutions that address the whole operations and standardized applications are needed.

6 Conclusion

This work aimed to find if digital twins can be leveraged for ESG reporting purposes and help in complying with the new ESRS reporting standards. Digital twin technology can be leveraged for ESG reporting through its ability to collect data on multiple levels and stages of the operations from the surrounding environment, supply chains and operations, combining different data sources and further aligning with ESRS standards. The findings of the work indicate that there is a significant potential for capturing and analyzing ESG data through digital twins. The largest potential was recognized in environmental and social reporting metrics, whereas for governance reporting, there was less potential found. Digital twins additionally have potential in supporting industry-specific reporting through specified applications, such as land management and marine digital twin systems.

Compliance with the reporting standards with digital twins can be supported through the ability of the DT technology to provide traceable data and to provide a retrospective look into the reporting areas. Furthermore, the benefits of increasing reporting quality and compliance are supported by the real-time and instantaneous report generation. Companies can showcase metrics instead of relying only on describing sustainability reports, due to digital twins making the sustainability data available. In addition to automating reporting processes, instead of manual data collection, estimations and calculations.

The area of digital twin applications is still developing, and new applications are emerging constantly. In addition to the developing ESG reports, which will most likely become even more extensive as companies adapt to the new regulations and sector-specific standards. Therefore, this work acts as a basis for future research in applying the technology for ESG reporting. Future research could be done more within the scope of social and governance reporting and developing an understanding of the ongoing reporting processes in the digital twins to generate the final report. The research could also explore the application of the technology in different industries. For the industry, this work gives great insight into the potential and limitations of the DT technology, especially as the extensive ESG reporting requires comprehensive reporting systems. Digital twins can also support companies in establishing their own sustainability metrics. Industry applications must also establish a view on whether to implement digital twins as part of reporting systems and to what extent.

6.1 Limitations of the research

It is acknowledged that at the point of writing this work the first phases of the CSRD have become applicable and the reports will develop in the upcoming years. For example, not all the companies chosen for the work have disclosed all mandatory information yet. Scope of the companies were small, although being from different industries. In addition, to the limitation on research papers as the topics is only recently established.

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