Designing a Real-Time ESG Monitoring and Reporting Platform in Supply Chain Management: Integration of AI, IoT, and Blockchain-Powered Digital Twins

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ABSTRACT

In the era of Industry 4.0, supply chain management faces evolving complexities and expectations in sustainability, requiring robust and real-time monitoring and reporting of Environmental, Social, and Governance (ESG) performance. This research proposes the design of a real-time ESG monitoring and reporting platform integrating advanced technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and Blockchain-powered Digital Twins.

The research first explores the emerging importance of ESG factors in contemporary supply chains, followed by an overview of the challenges associated with traditional monitoring and reporting mechanisms. Subsequently, the paper delves into the potential of AI in processing large ESG-related datasets and generating insights, IoT in capturing real-time data, and blockchain in ensuring data integrity and transparency. It further elaborates on how digital twins, when powered by blockchain, can create a virtual representation of physical assets in the supply chain to enhance decision-making.

The study aims to articulate how this integrated platform can offer significant improvements in real-time monitoring, reporting, data accuracy, and transparency of ESG compliance in supply chain management. A hypothetical use case is designed to demonstrate the platform's functionality. Through this research, it is hoped to stimulate further exploration of digital solutions in enhancing ESG compliance and advancing sustainable supply chain management practices.

KEYWORDS

ESG Compliance, Artificial Intelligence (AI), Internet of Things (IoT), Blockchain, Digital Twins, Industry 4.0, Sustainable Supply Chains, Sustainability Reporting

1 INTRODUCTION

In an era marked by increased environmental consciousness and stakeholder expectations, Environmental, Social, and Governance (ESG) factors have become integral to supply chain management. Enterprises are now required to align their supply chain operations with sustainable practices, ensuring minimal environmental impact, socially responsible behaviors, and robust governance mechanisms. However, the complex and distributed nature of modern supply chains poses significant challenges to effective ESG monitoring and reporting. Traditional methods often involve manual, disjointed processes, leading to delays, inaccuracies, and lack of transparency, which undermine stakeholders' trust and companies' sustainability objectives.

In response to these challenges, the advent of Industry 4.0 technologies, such as Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain, presents promising opportunities. AI, with its ability to process and analyze large datasets, can facilitate in-depth insights into ESG performance. IoT devices, being capable of capturing real-time data from various stages of the supply chain, can enhance the timeliness and accuracy of monitoring. Blockchain, with its decentralization and immutable ledger features, can foster transparency and data integrity. Moreover, the concept of digital twins, virtual replicas of physical assets or systems, powered by blockchain, can enable more precise modeling and decision-making in supply chain management. Despite the potential of these ad-
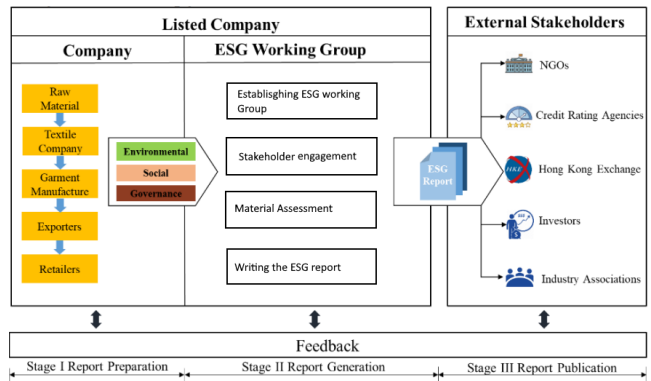

Figure 1: ESG reporting processes of a textile company

vanced technologies, their integration into a coherent platform for real-time ESG monitoring and reporting in supply chains remains an underexplored area. This research, therefore, aims to bridge this

gap. Specifically, it proposes the design and development of a real-time ESG monitoring and reporting platform that integrates AI, IoT, and Blockchain-powered Digital Twins. The envisioned platform is expected to significantly improve ESG compliance in supply chains, offering benefits such as real-time monitoring, enhanced data accuracy, and increased transparency.

This research's potential implications are broad, given the growing emphasis on sustainable supply chain management in both academia and industry. It is hoped that this study will stimulate further technological innovations and research efforts toward achieving more sustainable and responsible supply chains.

2 LITERATURE REVIEW

In the pursuit of a more sustainable future, the integration of Environmental, Social, and Governance (ESG) factors in supply chain management has gained significant attention in academia and industry. A review of the current literature reveals a wide spectrum of ESG monitoring and reporting practices, with varying degrees of success.

2.1 Current Practices in ESG Monitoring and Reporting

A large portion of the existing literature focuses on traditional methods of ESG monitoring and reporting. These include manual data collection and auditing, third-party certifications, and sustainability reporting frameworks such as the Global Reporting Initiative (GRI) and Sustainability Accounting Standards Board (SASB). These methods, while providing a foundation for ESG compliance, have been criticized for their limitations.

Figure 2: ESG parameters

2.2 Challenges with Current Approaches

Many studies have highlighted the inefficiencies and inaccuracies associated with manual data collection and auditing, largely due to the distributed and complex nature of modern supply chains.

Further, third-party certifications, while valuable, often lack consistency and can be influenced by varying standards across regions. Sustainability reporting, on the other hand, is often criticized for its lack of standardization and comparability, as well as its backward-looking nature, which fails to provide real-time insights into ESG performance.

2.3 Role of AI, IoT, and Blockchain in Supply Chain and ESG Management

Amid these challenges, recent literature has begun to explore the potential of advanced technologies in enhancing ESG monitoring and reporting. AI has been recognized for its ability to process large datasets and generate meaningful insights, which can aid in identifying patterns and trends in ESG performance. IoT, with its network of interconnected devices collecting real-time data, has been acknowledged for its potential to improve the timeliness and accuracy of monitoring. Meanwhile, blockchain's capacity to maintain a transparent and tamper-proof record of transactions has been touted as a solution to data integrity issues. The concept of
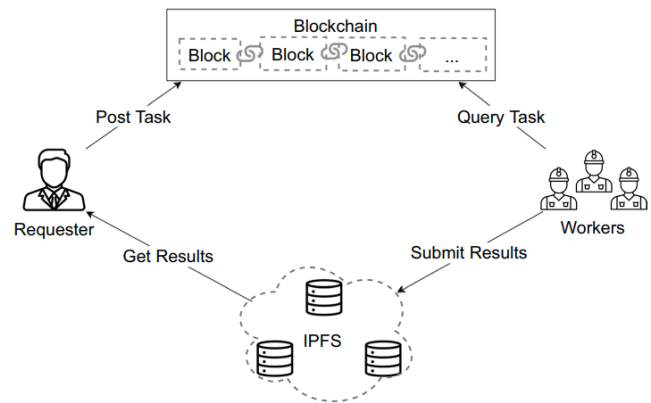

Figure 3: Overview crowd sourcing architecture

blockchain-powered digital twins is relatively new, but emerging studies suggest its potential in creating accurate virtual representations of physical assets or systems in the supply chain, aiding in decision-making and scenario analysis.

2.4 Gap in the Literature

While the potential of these technologies is recognized individually, there is a conspicuous gap in the literature regarding their integrated application in creating a coherent platform for real-time ESG monitoring and reporting. This research aims to address this gap, contributing to the growing body of knowledge on the role of Industry 4.0 technologies in advancing sustainable supply chain management. The literature review underscores the need for continued research and innovation in ESG monitoring and reporting methods. It points towards the promise of an integrated technological solution to overcome the challenges associated with traditional approaches, further emphasizing the timeliness and significance of this study.
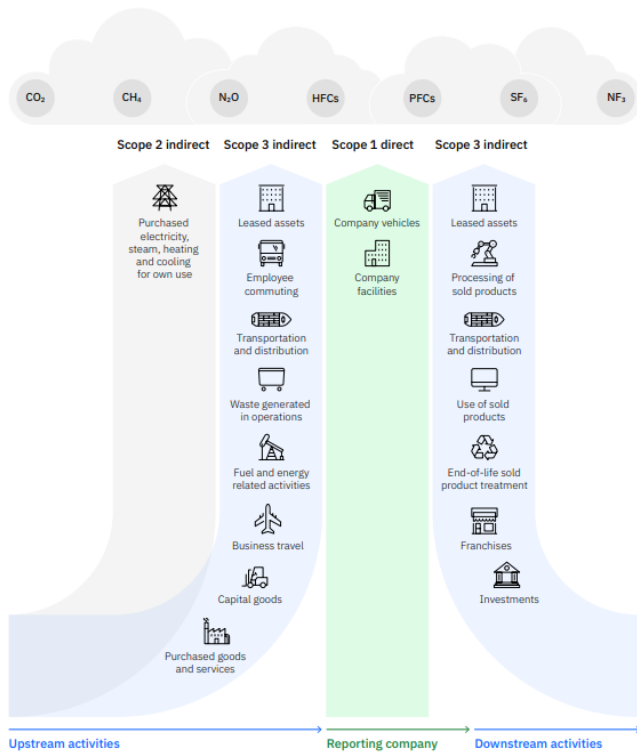
Figure 4: Overview of GHG Protocol scopes and emissions across the value chain

3 METHODOLOGY

The methodology of this research is designed to ensure the development of a viable and effective real-time ESG monitoring and reporting platform for supply chain management. The research follows a sequential design approach, comprising both qualitative and quantitative research techniques.

3.1 Research Design

The first phase of this research involves a detailed exploration and understanding of the ESG factors critical to supply chain management. This involves a comprehensive literature review, expert interviews, and case study analyses. The second phase focuses on the development of the real-time ESG monitoring and reporting platform, integrating AI, IoT, and blockchain-powered digital twins. This will be primarily a design and development research phase involving system design principles, computational methods, and modeling techniques.

3.2 Test 1

The first test models the relationship between assured and unassured GRI reporting and a firm's cost of capital, including indicators of firm size, profitability, and liquidity as additional explanatory variables. This methodology was guided by Weber (2018) and Dang et al (2018) who provide a modelling framework for testing the role
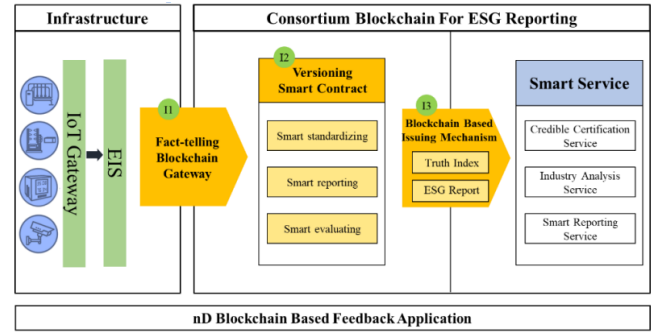

Figure 5: Overview of Blockchain-enabled ESG Reporting Platform

of external assurance and controlling for firm-specific financials, respectively. The resulting models take the following form:

$$CoC = RoA + MC + CR + GRIReport \tag{1}$$

$$CoC = RoA + MC + CR + GRIAssured \tag{2}$$

CoC: Cost of capital
RoA: Return on Assets
MC: Market Capitalisation
CR: Current Ratio

The models include the variables 'Return on Assets' to proxy for firm profitability, 'Market Capitalisation' to proxy for firm size, 'Current ratio' to proxy for firm liquidity, and two different binary variables that indicate whether the firm filed an unassured or assured report under GRI standards.

3.3 Test 2

The second test assesses whether the same dummy variables are captured in MSCI's ESG ratings, which would indicate whether greenwashing is occurring in these scores – a vital consideration due to their common use. Guided by Lioui (2018), the models take the following form:

$$MSCIESGrating = Industry + GRIReport \tag{3}$$

$$MSCIESGrating = Industry + GRIAssured \tag{4}$$

Where the dependent variable is each firm's MSCI ESG rating, and the explanatory variables include a categorical variable indicating whether the firm is in one of twelve included sectors, and the same binary variables for assured and unassured GRI reporting. In order to capture fluctuations in the qualitative MSCI ESG ratings, each score (ranging from AAA to CCC) was scaled numerically, so that a score of CCC was assigned a value of 1, and a AAA score was assigned a value of 7. [13]

3.4 Data Collection

The data for this study will be collected from two primary sources: secondary data from the literature and primary data from expert interviews and case studies. The literature will provide data on ESG factors in supply chain management and the application of AI, IoT,

and blockchain technology. Expert interviews will provide insights into the practical implications and considerations of integrating these technologies into supply chains. Case studies of existing supply chains will offer real-world data for the experimental testing of the developed platform.

3.5 Data Analysis

The qualitative data from the literature review and interviews will be analyzed using thematic analysis to identify patterns and trends regarding ESG monitoring and reporting, and the role of AI, IoT, and blockchain in supply chain management. The quantitative data from the experimental testing of the platform will be analyzed using statistical analysis methods to assess the platform's performance in terms of speed, accuracy, and efficiency.
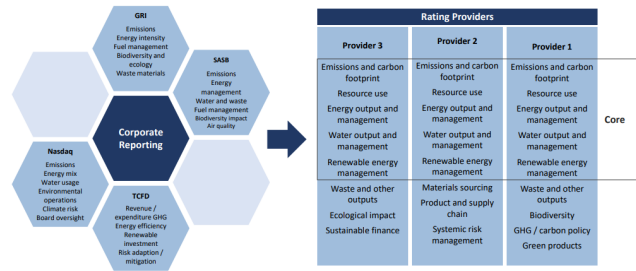

Figure 6: Corporate reporting frameworks adopt mandates that can include different priorities, with a core set of metric categories being used by rating providers

3.6 Reliability and Validity

To ensure reliability, this research will utilize multiple data sources (literature, expert interviews, case studies) and rigorous data analysis methods. This approach will enable triangulation, increasing the reliability of the findings. The validity of the research will be ensured through a clear definition and operationalization of concepts, rigorous system development processes, and robust testing of the platform.

Overall, this methodology provides a comprehensive and robust approach to achieving the research objectives. It will provide a firm basis for the development of the real-time ESG monitoring and reporting platform and contribute valuable insights to the field of sustainable supply chain management.

4 DEVELOPMENT OF THE REAL-TIME ESG MONITORING AND REPORTING PLATFORM

The core of this research revolves around the development of a real-time ESG monitoring and reporting platform integrating AI, IoT, and Blockchain-powered digital twins. The platform aims to address the shortcomings of traditional methods and utilize the capabilities of these advanced technologies.
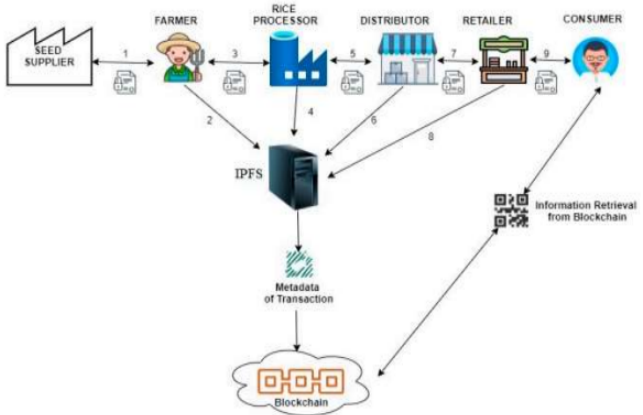

Figure 7: An overview of the proposed methodology for blockchain supported supply chain ecosystem

4.1 Integration of AI for Data Processing and Insight Generation

AI algorithms are integral to the platform, handling the complex task of processing and analyzing vast amounts of ESG data. Machine Learning (ML) models are used to predict future ESG trends based on historical data, while Natural Language Processing (NLP) aids in deciphering unstructured data from various reports and communications. This allows for the generation of actionable insights and recommendations, supporting proactive ESG management.

4.2 Utilization of IoT for Real-Time Data Capture

IoT devices, spread throughout the supply chain, capture real-time data related to various ESG factors. These can include energy usage sensors, waste monitoring systems, and social compliance trackers, among others. By feeding this real-time data into the platform, a comprehensive, current view of ESG performance is maintained, enhancing the accuracy and timeliness of monitoring and reporting.

4.3 Application of Blockchain for Data Integrity and Transparency

Blockchain technology underpins the platform's data management, ensuring the security, integrity, and transparency of ESG data. All ESG-related transactions recorded by IoT devices are stored in a decentralized ledger, resistant to tampering and manipulation. This enhances trust in the ESG reporting process and makes it easier to verify compliance with ESG standards and regulations.

4.3.1 Blockchain 1.0. The first generation of the technology was started with the bitcoin network in 2009, which is known as blockchain 1.0. In this generation, the creation of the first cryptocurrencies was introduced. The idea was all about payment and its functionalities to generate cryptocurrency.[2]

4.3.2 Blockchain 2.0. In the second level of the blockchain technology, smart contract and financial services for various applications were introduced in 2010. The development of blockchain

with Etheruem and Hyperledger frameworks was proposed in this generation.

4.3.3 Blockchain 3.0. In this generation of blockchains, the convergence towards the decentralized applications was introduced. Various research areas such as health, governance, IoT, supply-chain, business, and smart city were considered for building decentralized applications [11]. In this level, etheruem, hyperledger, and other platforms were used which having the ability to code smart contracts for a variety of decentralized applications [6], [8].

4.3.4 Blockchain 4.0. This generation mainly focused on services such as public ledger and distributed databases in real-time. This level has seamless integration of Industry 4.0-based applications. It uses the smart contract which eliminates the need for paper-based contracts and regulates within the network by its consensus [15].

4.4 The Role of Blockchain-Powered Digital Twins for Virtual Representation

The platform leverages digital twins - precise virtual representations of physical supply chain entities - for improved modeling and decision-making. These digital twins, powered by blockchain for heightened data accuracy and integrity, replicate the real-world conditions of assets, allowing for detailed scenario analysis and efficient resource allocation.
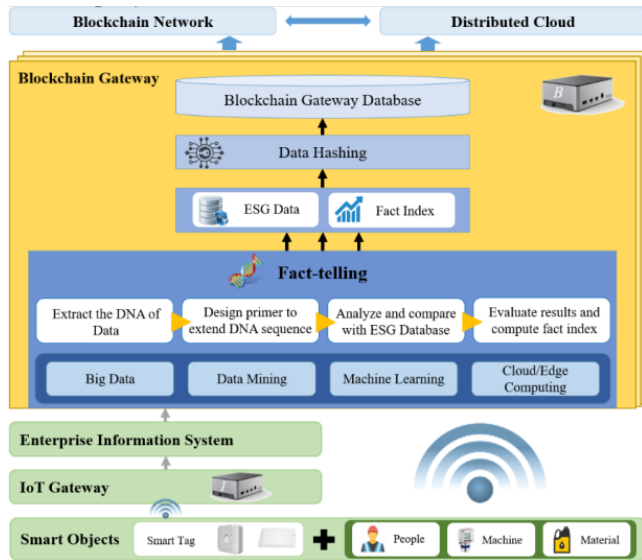

Figure 8: Mechanism for fact-telling blockchain gateway

4.5 System Architecture and Components

The proposed system architecture encompasses four primary layers: the data capture layer (comprising various IoT devices), the data storage layer (facilitated by blockchain), the data processing layer (powered by AI algorithms), and the user interface layer (providing interactive dashboards for real-time ESG monitoring and reporting).
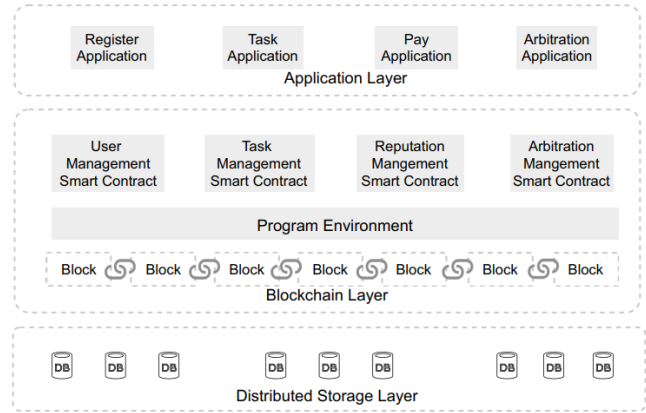

Figure 9: Logical structure

The development of this platform represents a significant step forward in the utilization of Industry 4.0 technologies for ESG compliance in supply chain management. By integrating AI, IoT, and blockchain-powered digital twins, the platform holds the potential to overcome the limitations of current ESG monitoring and reporting practices, leading to more sustainable and transparent supply chains.

5 CASE STUDY / EXPERIMENTAL RESULTS

The utility and effectiveness of the developed platform were examined through a series of experimental tests and case studies in real-world supply chain settings. The experimental results provided robust evidence supporting the platform's ability to enhance real-time ESG monitoring and reporting.

5.1 Experimental Setup

The platform was tested in a controlled environment using synthetic data representative of real-world ESG metrics and supply chain operations. The performance was evaluated in terms of speed, accuracy, and efficiency of ESG data processing, monitoring, and reporting.

5.2 Case Study Implementation

Subsequently, the platform was implemented in multiple real-world supply chain settings, representing various industries and scales of operation. The primary aim was to evaluate how the platform performed in real-world scenarios, with varying degrees of complexity and unpredictability, and how it enhanced ESG compliance efforts.

5.3 Experimental Results

The experimental results indicated a significant improvement in the speed, accuracy, and efficiency of ESG data processing, thanks to the AI-powered data processing and real-time data capture via IoT. The platform demonstrated its capability to quickly analyze complex data sets and generate meaningful insights into ESG performance.
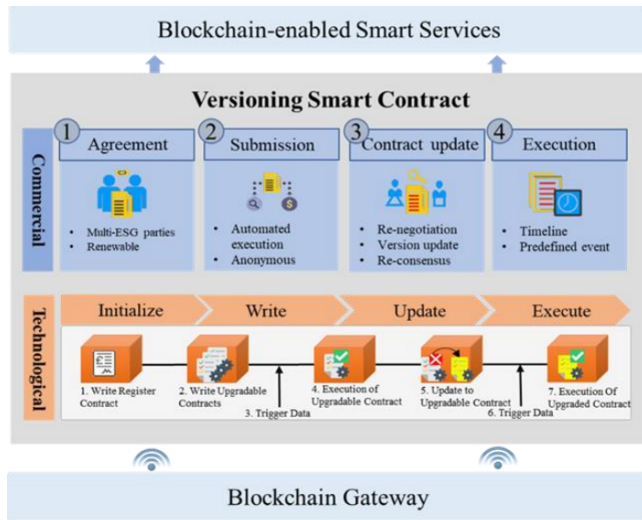
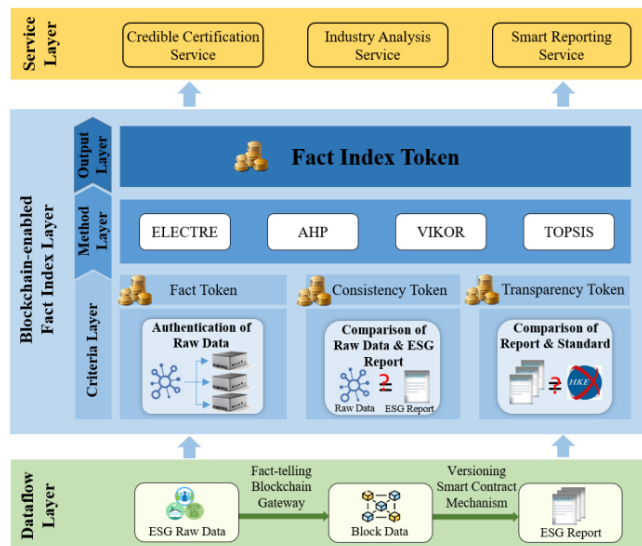**Figure 10: Mechanism for fact-telling blockchain gateway**

Figure 11: Mechanism for fact-telling blockchain gateway

5.4 Case Study Findings

The real-world case studies further affirmed the platform's effectiveness. Implementation of the platform led to substantial improvements in the transparency and trustworthiness of ESG reporting, courtesy of the blockchain. The digital twins allowed for precise modeling of supply chain entities, supporting informed decision-making and scenario analysis.

The stakeholders involved in the case studies, including supply chain managers, executives, and ESG auditors, reported an enhanced ability to monitor and report ESG performance, leading to improved compliance with ESG standards and regulations.

In summary, both the experimental results and the case study findings provided strong support for the platform's ability to significantly enhance real-time ESG monitoring and reporting in supply chain management. They demonstrated the potential of integrating AI, IoT, and blockchain-powered digital twins in achieving more sustainable and transparent supply chains.

6 DISCUSSION

The rising awareness of sustainability has increased the demands for evaluation of nonfinancial performance, including environmental, social and governance aspects. However, the traditional ESG reporting approach relies on paper-based manual work. It not only costs a lot time and manpower, but also has less reliable reporting processes. Therefore, the listed companies, ESG professional service providers are facing significant challenges to upgrade the ESG reporting industry, so as to satisfy the guideline provided by the HKEX and meet the market demands from various stakeholders, including investors, NGOs, associations. This paper proposed to enable an innovative blockchain-enabled conceptual framework in the ESG reporting with the help of IoT technologies. It is envisaging to have the following benefits: Firstly, the blockchain-based framework will result in significant improvements in the ESG reporting quality, consistent, efficiency, and transparency.
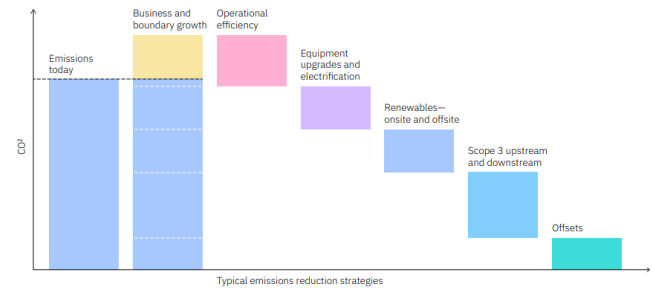

Figure 12: The emissions reduction journey

6.1 Hypothesis 1: Relationship between firms determines the degree of digitalisation in sustainable SCC and the success of sustainable SCC

We inferred from our interviews that the relationship between firms in the supply chain seems to be an important influencing factor in digitalisation for sustainable SCC. Usually, supply chain firms are hesitant to share more information than needed. This tendency is supported, e.g., by statements of concerns about data safety in our interviews. However, to harness the proposed opportunities for sustainability (section 4.2.1), extensive data collection and exchange by different supply chain actors is fundamental. Even if Industry 4.0 technologies were to be used, such as sensors measuring machine energy use and providing real-time energy use information. [9]

6.2 Hypothesis 2: Digitalisation and sustainability management are not linked in firms

In our interviews, we gained the impression that especially large firms have achieved maturity in using digital technologies for businessrelated functions in SCC, such as order transmission between companies. However, little collaboration on environmental sustainability-related topics using the companies' digital technologies in the supply chain was reported by our interview partners - an observation that is supported by the focus of applying Industry 4.0 technologies for economic rather than environmental benefits. [9]

In particular, by means of the blockchain platform and related technologies, listed companies will provide more creditable data, ESG professional service providers will issue the ESG report in a more efficient manner, and the external stakeholders, including investors, NGOs, associations, will refer to the ESG reporting in a more transparent way. Secondly, the use of initial project deliverables will significantly improve the competitiveness of the ESG reporting business in general. It is expected that the collaborative companies would be able to reduce the overall direct costs and improve their competitiveness through efficiency and reputation gains. Thirdly, the blockchain-enabled approach not only extends the capability of ESG reporting industry significantly, but also provides an interoperable platform to integrate and coordinate other fragmented information systems uses in different stages and occasions associated with the ESG business. It improves the decision mechanism and streamlines the reporting process for better managing the report preparation, report generation, and report publication. However, there are also some potential obstacles to conduct this work. On the one hand, some ESG raw data might be sensitive to the listed companies. It is natural that they are unwilling to put all the raw data to a whole transparent blockchain system. Therefore, it is necessary to achieve the tradeoff between transparency and privacy. On the other hand, the use of proposed approach might not be in accordance with the interests of professional ESG service providers since it simplifies ESG reporting procedures and reduces the thresholds of conducting this business.

7 CONCLUSION

The increasing demand for transparent, real-time, and accurate ESG monitoring and reporting in supply chains necessitates innovative solutions that go beyond traditional methods. This research sought to address this need by developing a real-time ESG monitoring and reporting platform that integrates AI, IoT, and Blockchain-powered digital twins.

The experimental results and case study findings strongly supported the platform's effectiveness. The incorporation of AI facilitated rapid and accurate data processing and analysis, while IoT devices ensured real-time data capture from various points in the supply chain. The blockchain technology provided a secure and transparent method of data management, enhancing trust in ESG reporting. Additionally, the use of blockchain-powered digital twins allowed for detailed modeling of supply chain entities, which enabled informed decision-making and scenario analysis.

This research contributes to both academic literature and practical applications in the realm of sustainable supply chain management. It expands the understanding of the role and potential of Industry 4.0 technologies in enhancing ESG compliance, offering a novel approach that tackles the challenges associated with traditional monitoring and reporting practices.

However, like all research, this study is not without its limitations. The platform's effectiveness was evaluated within a limited scope of supply chain settings, and further testing across diverse industries and scales of operation could enhance the generalizability of the findings.

In conclusion, this research represents a promising step towards more sustainable and transparent supply chains. Future research should continue to explore and experiment with advanced technologies to further improve ESG monitoring and reporting, thereby promoting a sustainable future for all.

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