BLOCKCHAIN-BASED DECISION SUPPORT SYSTEM FOR MEASURING ENVIRONMENTAL AND SOCIAL SUSTAINABILITY IN THE SUPPLY CHAIN

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DECLARATION OF ORIGINALITY

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ABSTRACT

Blockchain-Based Decision Support System for Measuring Environmental and Social Sustainability in the Supply Chain

Globalization has caused supply chains to become more complex and has created problems of misinformation, lack of transparency, traceability, and control. There is an inappropriate use of natural resources and exploitation of people and the environment at lower-tier levels of opaque value chains. Companies are pressured to be held accountable for these malpractices at the lower-tier levels of their suppliers. Consumers and governments demand that organizations reveal the environmental and social impacts of their supply chain activities. It is expected from companies to transform their business models to prioritize transparency and the environmental and social sustainability of their operations. Blockchain technology offers the essential properties that can make this transformation possible, it enables transparency, traceability, security, and real-time information sharing across supply chain participants. It has the potential to overcome the challenges in sustainable supply chain management. In this thesis, a quantitative sustainability measurement model for the environmental and social sustainability of supply chains is presented. Subsequently, a blockchain-based decision support system is developed to track and trace products throughout the supply chain and assess the environmental and social sustainability of the products and supply chain actors. Companies can use this system to gain more information about their supply chain activities and measure their sustainability performance.

ÖZET

Tedarik Zincirinde Çevresel Ve Sosyal Sürdürülebilirliği Ölçmek İçin Blokzincir Tabanlı Karar Destek Sistemi

Küreselleşme, tedarik zincirlerinin daha karmaşık hale gelmesine sebep oldu ve şeffaflık, izlenebilirlik ve kontrol eksikliği sorunlarını yarattı. Doğal kaynakların uygunsuz bir şekilde kullanılması ve alt seviyelerdeki opak tedarik zincirlerinde insanların ve çevrenin sömürülmesi söz konusudur. Şirketler, tedarikçilerinin alt kademelerinde bu yanlış uygulamalardan sorumlu tutulmalıdır. Tüketiciler ve hükümetler, kuruluşların ürünlerinin ve tedarik zinciri faaliyetlerinin çevresel ve sosyal etkilerini açığa çıkarmalarını talep etmektedir. Bu yüzden, geleneksel tedarik zincirlerinin radikal bir değişime ihtiyacı vardır. Şirketler, operasyonlarının çevresel ve sosyal sürdürülebilirliğini ve şeffaflığını ön planda tutacak şekilde iş modellerini değiştirmelidirler. Blokzincir teknolojisi, tedarik zinciri katılımcıları arasında şeffaflık, izlenebilirlik, güvenlik ve gerçek zamanlı bilgi paylaşımını sağlayan özellikler sunar. Sürdürülebilir tedarik zinciri yönetimindeki zorlukların üstesinden gelme potansiyeline sahiptir. Bu tezde, tedarik zincirlerinin çevresel ve sosyal sürdürülebilirliği için nicel bir sürdürülebilirlik ölçüm modeli sunulmaktadır. Sonrasında, tedarik zinciri boyunca ürünleri izlemek ve tedarik zinciri aktörlerinin çevresel ve sosyal sürdürülebilirliğini değerlendirmek için bir blokzincir tabanlı karar destek sistemi geliştirilmiştir. Şirketler, tedarik zinciri faaliyetleri hakkında daha fazla bilgi edinmek ve sürdürülebilirlik performanslarını ölçmek için bu sistemi kullanabilirler.

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ABBREVIATIONS

SSCM	Sustainable Supply Chain Management
DSS	Decision Support System
SDGs	Sustainable Development Goals
SLR	Systematic Literature Review
DSR	Design Science Research
GHG	Greenhouse Gas
PoW	Proof-of-Work
PoS	Proof-of-Stake
IPFS	InterPlanetary File System

CHAPTER 1

INTRODUCTION

The advent of globalization has enabled businesses to operate on an international scale stimulating global trade. Global trade is the import and export of goods and services throughout the supply chains around the world (OECD, n.d. -a). Despite the high economic growth, globalization has caused supply chains to become more complex and has created information asymmetry and lack of transparency. Outsourcing of goods and services has resulted in fragmented manufacturing and distribution systems, causing companies to lose control over their lower-tier suppliers (Vurro et al., 2009). Today there is a significant issue of trust between institutions (Saberi et al., 2019; Lim et al., 2021). The absence of transparency in the value chain hinders the exchange of accurate information (Lim et al., 2021). Dark side of globalization escalated this distrust between corporations due to being exposed to corporate misbehavior, unfair practices, and unethical conduct (Vurro et al., 2014; Kaplinsky, 2000). Today's opaque supply chains conceal global humanitarian problems. These include child labor, modern slavery, hazardous working conditions, discrimination, and mistreatment of women (ILO, 2019; Oxfam, 2019; UN Women, 2020; Hodal, K., 2020). In 2013, the poor labor conditions in the Rana Plaza, Bangladesh killed more than 1,132 individuals and wounded over 2,500 mostly girls and women (ILO, 2017). The children are being forced to work in cacao farms in Burkina Faso, cobalt mines in Congo, and cotton farms in India (UNICEF, 2020; Whoriskey et al., 2019). An estimated 200,000 migrant workers in the Thai fishing industry are victims of forced labor and modern slavery (Dow, 2019).

Furthermore, we are facing a planetary crisis, a threat to the existence of our civilization, known as climate change. Since the industrial revolution, human activities are leading to greenhouse gas emissions which are the primary reason of climate crises (Deloitte, 2021). The fossil fuel production companies are responsible for 42 percent of greenhouse gas emissions globally (Beck et al., 2020). Burning fossil fuels, and deforestation are the main activities that lead to the rapid increase in the GHGs concentration in the atmosphere. According to the Nobel Prize winner, Al Gore, the cost of ignoring this challenge is enormous, and soon would be unsustainable and unrecoverable. Climate change is already disrupting many Earth systems, contributing to desertification, sea-level rise, ocean acidification, poor air quality, and biodiversity loss (Deloitte, 2021). Also, the occurrence and intensity of natural disasters such as floods, wildfires, hurricanes, and droughts are increasing due to climate crises (European Commision, n.d.).

These horrifying events show that current supply chain systems are unsustainable. The global corporations that claim to follow ethical values lack the openness required to abide by their declarations and operate in a sustainable manner (Ndubisi & Nygaard, 2018). These threats make it evident that we must act immediately to accelerate the transition to a sustainable future (Guterres, 2020). Thus, businesses that rely on “outdated” and unsustainable supply chain practices need to radically change their business models and transform them into more agile, transparent systems that consider green and social sustainability solutions. Otherwise, the damage to global value chains on our planet would be irreversible and would put the life of future generations in jeopardy. To cope with these unsustainable global value chain practices, sustainability standards have emerged (Muradian & Pelupessy, 2005). Even though sustainability standards and certifications attempt to limit unethical corporate behavior and encourage responsible and sustainable global supply chains, their effectiveness and relevance are questioned (Bush et al., 2015).

More stakeholders demand businesses transition their operations and practices to be more environmentally and socially responsible (Srivastava, 2007; Tay et al., 2015). In 2015, United Nations (n.d.) introduced a universal framework for sustainable development to address the global economic, social, and environmental challenges our planet is currently facing. Sustainable Development Goals (SDGs) are a call for action for businesses to apply this framework in their operations (United Nations, n.d.). Some of the 17 global goals aim to end poverty and hunger, fight inequality, promote education, sustainable consumption and production, and address climate crises. In 2019, the European Union launched the European Green Deal to be climate neutral by 2050 (European Commision, 2019). The plan includes circular economy, sustainable and traceable supply chains, clean energy transition, pollution elimination, and protection of biodiversity.

According to Kouhizadeh and Sarkis (2018), to achieve sustainability both globally and locally, the way supply chains are managed must undergo a significant change. Supply chain actors need to measure their environmental and social sustainability performance and declare the origin of their products. For sustainability, every participant in the supply chain networks must work together and exchange information with each other (Gardner et al., 2019). However, there is always a possibility of data manipulation and discrepancy in sustainability performance measurement which may lead to dishonest results. Thus, to overcome these challenges there is an immediate need for a transparent and reliable platform that would earn the trust of the value chain actors and the shared information.

A system that offers the essential properties to ensure transparent and reliable data sharing for supply chain members is blockchain. Researchers claim that blockchain has the potential to radically transform the way global trade is currently organized, as well as to pave the way for a new economic and social system (Brakeville & Perepa, 2016; Swan, 2015). As Kshetri (2018) implies, by using blockchain technology key supply chain objectives such as cost, speed, dependability, risk reduction, sustainability and flexibility are fulfilled. Stakeholders can monitor and trace the sustainability performance of suppliers and the shipping of raw materials, as well as the location and timing of manufacturing, without the need for an intermediary entity. As a result, from the beginning to the end of the supply chain journey, all concerned parties can access the necessary information through the recorded data and transactions in the blockchain. Due to the blockchain's tamper-proof feature, parties will be confident that the shared information is reliable. With QR-codes attached to the product, the customers can gain access to information about the environmental and social sustainability of the product and how it was manufactured and sourced. Academic literature acknowledges the significance of effective use and adoption of new technologies in enabling more efficient and responsible production practices and achieving the SDGs (UNEP, 2015). With these motivations, this research aims to develop a blockchain-based decision support system (DSS) to measure the environmental and social sustainability performances of the supply chain. It aspires to answer the following research questions:

- How are environmental and social sustainability measured in the supply chain? What are the measures and the tools used?

- How does blockchain adoption make a difference in measuring environmental and social sustainability? What are the benefits and challenges?
- How to integrate blockchain to measure the environmental and social performance of the supply chain more efficiently, effectively and flexibly?

This research aspires to contribute to the literature in two ways. First, it intends to improve the environmental and social sustainability indicators in sustainable supply chain management. Secondly, it aims to fill the gap of a blockchain-based decision support system that measures sustainable supply chain performance.

The remainder of the thesis is structured as follows. In Chapter 2, a literature review on environmental and social sustainability metrics and tools used in sustainable supply chain management is given. Subsequently, the benefits and challenges of blockchain technology in sustainable supply chain management are explored. Later, a brief background on blockchain technology is presented in Chapter 3. In Chapter 4, the methodology applied in this thesis is described and is followed by the development and implementation of the blockchain-based DSS in Chapter 5. Consequently, the performance of the blockchain based DSS is evaluated in Chapter 6. Lastly, the thesis is concluded with final remarks comprising the research findings, limitations and future research recommendations.

CHAPTER 2

LITERATURE REVIEW

This chapter starts with an introduction to sustainability and sustainable supply chain management. Subsequently, it describes the literature on sustainability performance measurement tools and environmental and social sustainability indicators. Afterward, it analyzes the benefits and barriers of blockchain technology in sustainable supply chain management.

2.1 Environmental and social sustainability measurement in SSCM

2.1.1 Sustainability

The word sustainability developed in the 17th century and was used for maintaining forest resources across Europe (Warde, 2011; Grober & Cunningham, 2012). However, sustainability and sustainable development concepts were introduced and widely accepted with the Brundtland Report issued in 1987 by the World Commission on Environment and Development (WECD). In the report, sustainable development was defined as "the development that meets the needs of the present without compromising the ability of the future generations to meet their own needs." (Brundtland, 1987, p. 37). In 1994, Elkington invented the phrase "triple bottom line (TBL)", a sustainability framework for businesses to measure their social and environmental impact along with their financial measurements. The three pillars of sustainability that form the triple bottom line are social development, environmental preservation, and economic development, also known as people, planet, and profit (Elkington, 1994). The three pillars are interdependent; one cannot exist without the other (Tay et al., 2015; Carter & Easton, 2011). Achieving a balance among the pillars requires a firm grasp of how society and industrial actions affect the environment, as well as how today's decisions may affect future generations (Hutchins & Sutherland, 2008). Figure 1 shows the interconnected relationship of the three dimensions of sustainability.

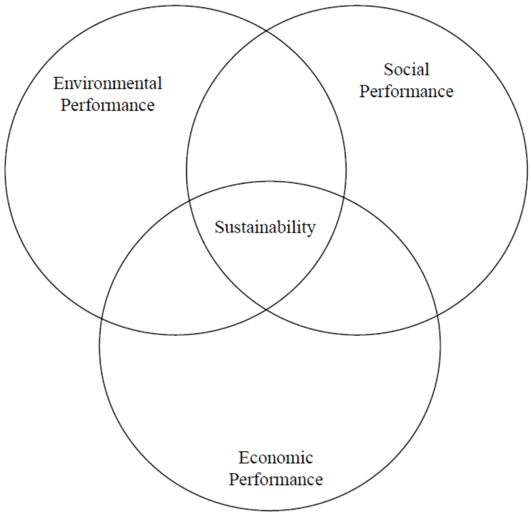


Figure 1. The triple bottom line
[Carter & Rogers, 2008]

2.1.2 Sustainable supply chain management

Sustainable supply chain management is described by Seuring and Müller (2008) as “the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development into account which are derived from customer and stakeholder requirements. In sustainable supply chains, environmental and social criteria need to be fulfilled by the members to remain within the supply chain, while it is expected that competitiveness would be maintained through meeting customer needs and related economic criteria” (p. 1700).

Social sustainability is related to the health and well-being of individuals participating or impacted by the value chain operations (Panigrahi et al., 2018).

Social sustainability covers issues on working conditions, avoiding exploitation of workers, fair wages, equal treatment, and freedom of association (Saberi et al., 2019).

The purpose of environmental sustainability for supply chains is to manage businesses so that no damage would come to the environment (Panigrahi et al., 2018). It is predicted that supply chain operations contribute to 90% of the overall environmental consequence (Carter et al., 2019).

The foundation of economic sustainability is the effective resource management and achieving a return on investment (Winter & Knemeyer, 2013). Managers need to examine operations for social and environmental sustainability that would provide long-term advancement and maintain economic progress (Carter & Easton, 2011).

According to Tate and Bals (2018), the economic part of TBL is widely employed by organizations; however, the environmental and social aspects are overlooked since they are difficult to assess.

2.1.3 Sustainability performance measurement tools in SSCM

Interest in the topic of sustainable supply chain management has increased as a result of recent environmental and social problems identified in supply chains, as well as pressure on sustainable practices (Seuring & Müller, 2008). Companies are under growing pressure to measure, regulate, and report their own and their suppliers' total sustainability performance (Qorri et al., 2018; Panigrahi et al., 2018; Manupati et al., 2020). They are held responsible for the whole performance of their supply chain. Performance measurement is known as “the practice of quantifying the efficiency and effectiveness of action” (Neely et al., 1995). By assessing and managing the sustainability of supply chains, organizations minimize expenses, boost efficiency, enhance competitiveness, facilitate sustainability reporting, boost business performance, and assist in strategy development (Qorri et al., 2018). It is emphasized that key SSCM principles of transparency, supplier evaluation, and collaboration are possible simply when relevant sustainability assessment and management methods are adopted (Beske-Janssen et al., 2015).

Evaluating the sustainability performance of supply chains across various stakeholders such as suppliers, manufacturers, and distributors is a complex and difficult task. The challenges may be due to the absence of guidance on ways to assess and use SSCM in company practices (Stindt, 2017). Schaltegger and Burrit (2014), mention the necessity for a sustainability framework that can be used by managers to improve the performance of their supply chain. Value chain managers should choose and aggregate indicators from a broad set of sustainability measures to help facilitate supply chain decisions related to sustainability (Bai & Sarkis, 2014).

Over the last three decades, the significance of supply chain sustainability has evolved, and it has become a primary factor of demand and consumer engagement (Kouhizadeh et al., 2021). There are presently sustainability auditing and certification organizations for supply chains. However, it has been debated whether these auditing organizations are capable of generating truly reliable, independent evidence (Boiral & Gendron, 2011). These problems have developed as a result of the fact that the auditors are frequently employed and paid by the organizations they are supposed to audit (Bazerman et al., 1997). This means that the success of an auditing firm is dependent on maintaining positive relationships with its clients (Lund-Thomsen & Lindgreen, 2014). Furthermore, a lack of systematic assessment and proper documentation is a major weakness of sustainability standards

(Giovannucci & Ponte, 2005). Due to the distributed value chain networks, there is difficulty in defining the complete value chain processes and all relevant actors throughout the chain (Muradian & Pelupessy, 2005). As a result, certification companies like Fair Trade coffee, has been unable to certify the whole production of all registered organizations, as the total certified sales amounted to only 13 percent of total registered production (Muradian & Pelupessy, 2005). Moreover, the implementation of certification and meeting the various requirements may incur significant costs (Giovannucci & Ponte, 2005). These economic consequences can be especially difficult for smaller suppliers, who typically have limited access to financial resources. Also, the assessment frameworks of sustainability standards may not be efficient. For example, GRI, ISO 14001, and ISO 26000 standards propose assessment frameworks for environmental and social sustainability performance. However, they do not cover all aspects of sustainability and are therefore insufficient (Chardine-Baumann & Botta-Genoulaz, 2014).

The methodologies offered in the literature for measuring the supply chain's sustainability performance are as follows: Balanced Scorecard (BSC), Life Cycle Assessment (LCA), Fuzzy set approaches, Data Envelopment Analysis (DEA), Supply Chain Operations Reference (SCOR) model, Analytic Hierarchy/Network Process (AHP/ANP) (Qorri et al., 2018). These approaches have been chastised for failing to address all sustainability dimensions (Hassini et al., 2012; Seuring, 2013), and almost all of the methods fail to integrate all supply chain actors (Ahi & Searcy, 2015).

The current literature is focused on LCA, the product life cycle method that uses macro data to estimate impacts of the produced products. The LCA approach is often used to assess environmental consequences related to all phases of the product life cycle from raw material procurement to manufacture, distribution, usage, and disposal (Rebitzer et al., 2004). Figure 2 illustrates the phases and applications of LCA.

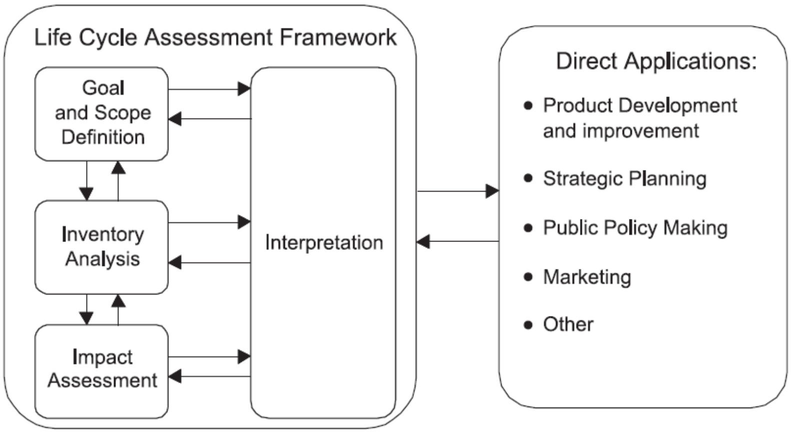


Figure 2. The phases and applications of LCA
[Rebitzer et al., 2004]

Businesses have utilized LCA to discover bottlenecks to lessen the environmental effect of their supply chain operations (Lake et al., 2015). It assists in the development of sustainable products and marketing that would guide consumer decisions (Levasseur et al., 2016).

According to Teh et al. (2020), organizations that conduct LCA on their products have the potential to boost the effectiveness of manufacturing and company operations. They can reduce raw material and energy consumption, better manage their waste, and create innovative eco-designed products, enhance their brand reputation, and customer loyalty.

However the current LCA practices use inventory data, from databases such as GaBi or Ecoinvent, instead of using actual product information related to its production. A better information model is required for sustainability measurement in supply chains that includes detailed, precise, trustworthy, and real-information of each supplier (Beske-Janssen et al., 2015). Businesses require a thorough sustainability assessment framework to achieve sustainability. Thus, a systematic literature review (SLR) is done concerning environmental and social performance indicators. The SLR is conducted according to the guidelines of Kitchenham (2004). The guidelines include steps of determining research questions, selecting articles, assessing the quality of the articles, data extraction and synthesis. After identifying research questions, search strings are chosen for the review. The search strings are derived from the first research question and are backed up by the keywords used in the previous studies (Beske-Janssen et al., 2015; Qorri et al., 2018). The keywords used in the search process were: “sustainable supply chain”, “supply chain sustainability”, “indicators”, “measures”, “metrics”, “sustainability assess*”, “sustainability measur*”. The systematic literature review focused on all peer-reviewed articles published in the Scopus database in the English language. Scopus is chosen because it includes a diverse variety of articles in sustainability and supply chain management (Ahi & Searcy, 2015; Govindan et al., 2020). The search identified 406 articles. In the elimination process duplicate and irrelevant papers were disregarded. The inclusion and exclusion criteria were established and the abstracts and full papers were screened. Articles that provided environmental or social sustainability performance indicators for supply chain were included. The papers that do not contain quantitative or qualitative environmental or social sustainability indicators were excluded. The quality of the found literature is assessed with the qualitative checklist proposed by Kitchenham (2004). After careful elimination, 21 articles were taken into account for further classification. The sustainability framework of GRI was also included in the classification. GRI is an international standard that assists companies in sustainability reporting (GRI, 2013).

Lastly, the articles were meticulously analyzed and synthesized to obtain the findings. It is observed that there is an absence of quantitative sustainability measures available especially in the social dimension. In most of the papers, only the indicators are mentioned by their name and there is no further explanation on how they are measured in actual practice. From the articles, frequently used environmental and social indicators were selected and for each indicator related quantitative measurements were acquired. Thus, a quantitative measurement framework for environmental and social sustainability performance is created. This resulted in 23 environmental and 25 social sustainability indicators.

2.1.4 Environmental sustainability assessment

The environmental aspect of sustainability is related to the influence of business operations on living and non-living ecosystems (GRI, 2013). The aim of the green supply chain management, according to Hervani et al. (2005), is to abolish or diminish the harmful environmental consequences such as pollution and wastes from raw material extraction to product end-use and disposal. The proposed environmental sustainability indicators consist of 23 indicators categorized under three groups; natural resources, pollution and waste management, and operations management and performance measurement (Table 1).

Table 1. Environmental Sustainability Performance Indicators

Indicator Category	Indicators	Sources
Natural Resources		
	Energy consumption	Erol (2011), GRI (2013), Govindan et al. (2013), Ahi & Searcy (2015), Tajbakhsh & Hassini (2015), Fritz et al. (2017), Saeed & Kersten (2020), Giannakis et al. (2020),
	Energy efficiency	Stindt (2017), Fritz et al. (2017), Kumar & Garg (2017), Gong et al. (2018), Saeed & Kersten (2020), Neri et al.
	Renewable energy	Erol (2011), GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Tajbakhsh & Hassini (2015), Stindt (2017), Fritz et al. (2017), Kumar & Garg (2017), Saeed & Kersten (2020), Neri et al. (2021)
	Water consumption	Erol (2011), GRI (2013), Govindan et al. (2013), Ahi & Searcy (2015), Tajbakhsh & Hassini (2015), Stindt (2017), Fritz et al. (2017), Saeed & Kersten (2020), Neri et al. (2021)
	Recycled/reused water	GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Fritz et al. (2017), Saeed & Kersten (2020), Neri et al. (2021)
	Material consumption	GRI (2013), Govindan et al. (2013), Stindt (2017), Saeed & Kersten (2020), Neri et al. (2021)
	Material efficiency	GRI (2013), Govindan et al. (2013), Stindt (2017), Kumar & Garg (2017), Saeed & Kersten (2020), Neri et al. (2021)
	Recycled/reused materials	Erol (2011), GRI (2013), Govindan et al. (2013), Chardine-Baumann & Botta-Genoulaz (2014), Ahi & Searcy (2015), Stindt (2017), Gong et al. (2018), Saeed & Kersten (2020), Neri et al. (2021)
	Land use	GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Stindt (2017), Saeed & Kersten (2020), Neri et al. (2021)
	Biodiversity	GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Ahi & Searcy (2015), Stindt (2017), Fritz et al. (2017), Neri et al. (2021)
Pollution and Waste Management		
	Greenhouse gas emission	GRI (2013), Govindan et al. (2013), Tajbakhsh & Hassini (2015), Ahi & Searcy (2015), Kumar & Garg (2017), Stindt (2017), Fritz et al. (2017), Gong et al. (2018), Saeed & Kersten (2020), Neri et al. (2021)
	Air pollution	GRI (2013), Govindan et al. (2013), Chardine-Baumann & Botta-Genoulaz (2014), Ahi & Searcy (2015), Neri et al.
	Water pollution	GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Neri et al. (2021)
	Land pollution	GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Neri et al. (2021)
	Use of hazardous materials	GRI (2013), Govindan et al. (2013), Chardine-Baumann & Botta-Genoulaz (2014), Ahi & Searcy (2015), Stindt (2017), Fritz et al. (2017), Saeed & Kersten (2020), Neri et al. (2021)
	Hazardous waste	GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Saeed & Kersten (2020), Neri et al. (2021)
	Solid waste	GRI (2013), Govindan et al. (2013), Chardine-Baumann & Botta-Genoulaz (2014), Ahi & Searcy (2015), Fritz et al. (2017), Kumar & Garg (2017), Gong et al. (2018), Saeed & Kersten (2020), Neri et al. (2021)
	Wastewater	GRI (2013), Govindan et al. (2013), Chardine-Baumann & Botta-Genoulaz (2014), Fritz et al. (2017), Kumar & Garg (2017), Gong et al. (2018), Saeed & Kersten (2020), Neri et
	Product recyclability	GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Stindt (2017), Gong et al. (2018)
	Green packaging and labeling	Kumar & Garg (2017), Luthra et al. (2017), Chardine-Baumann & Botta-Genoulaz (2014)
Operations Management and Performance Measurement		
	Environmental management system (ISO 14001)	UNGC (2000), Govindan et al. (2013), Chardine-Baumann & Botta-Genoulaz (2014), Ahi & Searcy (2015), Stindt (2017), Fritz et al. (2017), Luthra et al. (2017), Saeed & Kersten (2020), Neri et al. (2021)
	Cleaner technology	UNGC (2000), Ahi & Searcy (2015), Tajbakhsh & Hassini (2015), Kumar & Garg (2017), Luthra et al. (2017)
	Supplier assessment	Erol (2011), GRI (2013), Gong et al. (2018), Saeed & Kersten (2020)

The natural resources category contains ten indicators. They constitute the raw materials that occur in nature that can be used for production.

Energy consumption is the total use of energy from sources such as coal, oil, natural gas, renewable energy, nuclear energy, etc (Ritchie & Roser, 2020). Non-renewable energy is a significant contributor to climate change. Energy efficiency is the energy reduction used. It is achieved either by reducing energy consumption during production or by developing products that use less energy over their lifetime. Renewable energy is the energy used from sources such as solar, hydro, wind, biomass, and geothermal energy.

Water consumption is the total use of water from ground or surface water sources (GRI, 2013). Recycled or reused water is the water that is used from recycling or reusing wastewater. It is an efficiency metric that measures a company's success in reducing overall water draws and discharges (GRI, 2013). Water consumption, treatment, and disposal expenses may be minimized due to improved reuse and recycling.

Material consumption is the total use of materials in production. Material efficiency is the reduction in materials usage. Businesses seeking to improve the efficiency of their material and energy flows would likely benefit from finding opportunities to reduce waste and unwanted byproducts (Stindt, 2017). Recycled or reused materials are the materials that are used from recycling or reusing discarded materials. Recycled or reused materials aids to diminish the need for raw materials while also contributing to the protection of global resources.

Land use covers the use of land and natural and semi-natural vegetation. Lack of awareness of the implications of land use and biodiversity might offer considerable economic hazards, as seen in industries that have been publicly chastised for deforestation associated with the manufacture of palm oil and leather (Vurro et al., 2009). Biodiversity contains all forms and varieties of life on Earth. The protection of biodiversity is to maintain the survival of all organisms, species, and populations, as well as the genetic diversity among them; and their complex communities and ecosystems.

The pollution and waste management category consists of ten indicators. Waste is produced at every stage of human activity. The stages include extraction of raw resources, processing of raw materials into intermediate and final goods, consumption of finished products, and so on. (OECD, n.d. -b). Inappropriate pollution and waste management have damaging impacts on human health and the environment.

Greenhouse gas emissions amplify the natural greenhouse effect, causing temperature fluctuations and other climate-related effects (OECD, n.d. -b). GHGs comprise seven gasses that have directly related to the climate change. They are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3). The emission data are articulated in CO_2 equivalents and denote gross direct emissions from human actions. Air pollution includes emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOC). Water pollution occurs from deliberate or accidental spills in surface waters and infiltrations in groundwater (GRI, 2013). Land pollution is the discharge of heavy metals, hydrocarbons, dioxins, and phenols. The use of hazardous materials is the harmful/toxic materials used during production.

Solid waste is the materials that are discarded after use (GRI, 2013). Wastewater is generated as a result of the use of freshwater. Hazardous waste is waste that is dangerous and that can damage human health or the environment. Product recyclability is the products produced that are recyclable. Green packaging and labeling indicate the products are manufactured with eco-friendly packaging and labeling.

The operations management and performance measurement category contain three indicators. Operational management deals with the design and control of manufacturing processes. The environmental management system indicates whether the company is certified to meet the standards of environmental regulations. The ISO 14001 certification is frequently utilized as the verification of environmental sustainability (Hervani et al., 2005). Cleaner technology is the use of environmentally friendly technologies, practices, and methods. By implementing environmentally friendly technologies, companies can reduce the use of raw materials, resulting in increased efficiency. Supplier sustainability assessment is the audit and assessment of the environmental performance of suppliers led by the company or other organizations.

2.1.5 Social sustainability assessment

The social dimension of sustainability is concerned with the organization's influences on the social systems where it functions (GRI, 2013). It is the most challenging pillar to analyze due to its difficulties in quantifying (Beske-Janssen et al., 2015). The Global Reporting Initiative (GRI) classifies social sustainability into four sub-categories: labor practices and decent work, human rights, society, and product responsibility. The social sustainability indicators consist of 25 indicators categorized under five groups; labor practices, health and safety, human rights, society, and product responsibility (Table 2).

Table 2. Social Sustainability Performance Indicators

Indicator Category	Indicators	Sources
Labor Practices		
	Employee training and development	Erol (2011), GRI (2013), Fritz et al. (2017), Stindt (2017), Kumar & Garg (2017), Chen & Holden (2017), Popovic et al. (2018), Siebert et al. (2018), Govindan et al. (2020), Saeed & Kersten (2020), Giannakis et al. (2020)
	Employee turnover	Erol (2011), GRI (2013), Stindt (2017), Popovic et al. (2018), Gong et al. (2018), Govindan et al. (2020), Saeed & Kersten (2020)
	Full and part-time employees	Popovic et al. (2018), Siebert et al. (2018)
	Hours of work	Kühnen & Hahn (2017), Chen & Holden (2017), Stindt (2017), Popovic et al. (2018), Siebert et al. (2018), Almanza & Corona (2020)
	Fair wage	Fritz et al. (2017), Kühnen & Hahn (2017), Chen & Holden (2017), Kumar & Garg (2017), Siebert et al. (2018), Almanza & Corona (2020)
	Social benefits and security	GRI (2013), Kühnen & Hahn (2017), Chen & Holden (2017), Popovic et al. (2018), Almanza & Corona (2020), Saeed & Kersten (2020)
	Gender diversity	Erol (2011), GRI (2013), Chen & Holden (2017), Stindt (2017), Popovic et al. (2018), Siebert et al. (2018), Almanza & Corona (2020)
	Diversity among workforce	Tajbakhsh & Hassini (2015), Chen & Holden (2017), Popovic et al. (2018), Siebert et al. (2018)
	Social standards (SA8000,	Erol (2011), Stindt (2017), Saeed & Kersten (2020)
Health & Safety		
	Occupational health and safety	GRI (2013), Tajbakhsh & Hassini (2015), Fritz et al. (2017), Stindt (2017), Kumar & Garg (2017), Kühnen & Hahn (2017), Chen & Holden (2017), Gong et al. (2018), Govindan et al. (2020)
	Accidents	Erol (2011), GRI (2013), Fritz et al. (2017), Popovic et al. (2018), Siebert et al. (2018), Saeed & Kersten (2020)
Human Rights		
	Freedom of association	UNGC (2000), GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Tajbakhsh & Hassini (2015), Fritz et al. (2017), Chen & Holden (2017), Stindt (2017), Kühnen & Hahn (2017), Popovic et al. (2018), Govindan et al. (2020), Almanza & Corona (2020)
	Collective bargaining agreements	UNGC (2000), GRI (2013), Tajbakhsh & Hassini (2015), Fritz et al. (2017), Chen & Holden (2017), Kühnen & Hahn (2017), Popovic et al. (2018), Almanza & Corona (2020)
	Discrimination	UNGC (2000), GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Fritz et al. (2017), Chen & Holden (2017), Stindt (2017), Kühnen & Hahn (2017), Popovic et al. (2018), Govindan et al. (2020), Saeed & Kersten (2020)
	Child and forced labor	UNGC (2000), GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Tajbakhsh & Hassini (2015), Fritz et al. (2017), Stindt (2017), Kühnen & Hahn (2017), Popovic et al. (2018), Almanza & Corona (2020)
	Rights of indigenous people	GRI (2013), Stindt (2017), Kühnen & Hahn (2017), Chen & Holden (2017), Popovic et al. (2018)
Society		
	Job localization	Chardine-Baumann & Botta-Genoulaz (2014), Chen & Holden (2017), Kühnen & Hahn (2017), Gong et al. (2018), Govindan et al. (2020), Almanza & Corona (2020), Saeed & Kersten (2020)
	Source localization	Tajbakhsh & Hassini (2015), Gong et al. (2018), Govindan et al. (2020), Saeed & Kersten (2020)
	Community development	Erol (2011), Chardine-Baumann & Botta-Genoulaz (2014), Tajbakhsh & Hassini (2015), Fritz et al. (2017), Stindt (2017), Kühnen & Hahn (2017), Chen & Holden (2017), Kumar & Garg (2017), Gong et al. (2018), Govindan et al. (2020), Giannakis et al. (2020), Almanza & Corona (2020)
	Corruption	UNGC (2000), GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Stindt (2017), Fritz et al. (2017), Kühnen & Hahn (2017), Govindan et al. (2020), Almanza & Corona (2020), Saeed & Kersten (2020)
	Anti-competitive behavior	GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Kühnen & Hahn (2017), Stindt (2017), Almanza & Corona (2020)
	Supplier sustainability assessment	(GRI, 2013), (Tajbakhsh & Hassini, 2015), (Almanza & Corona, 2020)
Product Responsibility		
	Customer health and safety	GRI (2013), Fritz et al. (2017), Stindt (2017), Kühnen & Hahn (2017), Govindan et al. (2020), Saeed & Kersten (2020)
	Respect for privacy	GRI (2013), Chardine-Baumann & Botta-Genoulaz (2014), Fritz et al. (2017)
	Customer complaints	Erol (2011), Fritz et al. (2017), Giannakis et al. (2020), Saeed & Kersten (2020)

The labor practices category contains nine indicators. Employee training and development are provided by the employer to enhance employees' skills and knowledge for improved performance, productivity, and career development (Siebert et al., 2018). Employee turnover measures the relationships between unions and employees. A good relationship is mirrored in a more pleasant working atmosphere, minimized operational interruptions, and reduced staff turnover (Popovic et al., 2018).

Full and part-time employee indicators can measure the relationship between employees and the company. The high number of full-time workers indicates a stronger relationship between the employees and the firm. Whereas, more part-time workers can indicate a weak relationship between the staff and the organization (Popovic et al., 2018). Work hours demonstrate the company's capability to comply with the national law, employees exceeding the authorized work hours may indicate a lack of staff (Popovic et al., 2018). Overtime work is the hours worked by an employee that exceeds the normal work hours. Extra work hours may affect the workers' health negatively causing fatigue that may contribute to an increase in the number of accidents and injuries, as well as decreased productivity and quality (ILO, n.d.).

Fair wage shows how much wage employees earn in their job compared to the national minimum wage. Social benefits and security indicate the number of employees entitled to health insurance, parental leave, unemployment, disability and invalidity coverage, and retirement provision (GRI, 2013; Popovic et al., 2018; Saeed & Kersten, 2020).

Gender diversity indicators show wage and employment equality between male and female employees as well as the company's initiative to ensure equal opportunities (Popovic et al., 2018). The diversity of the workforce demonstrates the company's dedication to human rights and its commitment to giving equal opportunity to all employees. Diversity in the workforce includes disabled employees (Popovic et al., 2018; Siebert et al., 2018), minority employees (Siebert et al., 2018), and older employees with age over 65 (Chen and Holden, 2017; Siebert et al., 2018). Social standards indicate whether the company is certified to meet the standards of social sustainability regulations. The SA8000 or ISO 2600 certification is used as an validation of social sustainability performance in supply chain (Ahi & Searcy, 2015).

Health and safety category consists of two indicators. Occupational health and safety is the organization’s agreement with ILO Guidelines for Occupational Health Management Systems (GRI, 2013; Tajbakhsh & Hassini, 2015). Further, the presence of fire-fighting tools and emergency exits, provision of medical assistance and first aid, access to drinking water and sanitation, and delivery of protective gear assessments are checked (Fritz et al., 2017; Almanza & Corona, 2020). Accidents indicate work accidents.

The human rights category contains five indicators. Freedom of association measures the existence of unions within a company (Almanza & Corona, 2020) and the number of employees who joined labor unions (Popovic et al., 2018). Collective bargaining agreements indicate legal agreements between the organization and the union representing the employees. Discrimination entails discrimination incidents based on “race, color, sex, religion, political opinion, national extraction, social origin, or other types of discrimination involving internal and external stakeholders across operations during the reporting period” (ILO, n.d.). The eradication of child labor and forced labor is the fundamental basis and goal of human rights regulations (GRI, 2013). The absence of violations of indigenous people's rights implies the organization's capacity to uphold basic human rights (Popovic et al., 2018).

Society category consists of six indicators. Job and source localization is the employment of local organizations and stakeholders, as well as the business community (Almanza & Corona). Community development is the organization’s financial investments for the benefit of the community.

Corruption is the misuse of assigned authority for personal gain (GRI, 2013). Bribery, conflict of interest, fraud, money laundering, concealment and obstruction of justice, and influence trading are all examples of corruption. Corruption can lead to violations of human rights, the deterioration of political processes, the poverty of societies, and environmental degradation (GRI, 2013).

Anti-competitive, antitrust, and monopolistic behaviors could have an impact on customer choice, pricing, and other market-relevant aspects. Many countries have enacted legislation to limit or avoid monopolies to enable fair competition among firms (GRI, 2013). Supplier sustainability assessment is the audit and assessment of the social performance of suppliers led by the company or other organizations.

Product responsibility category consists of three indicators. Customer health and safety identifies the regular attempts to maintain health and safety across a product's life cycle (GRI, 2013). Companies are responsible for the health and safety of those who use or deliver their products or services. Respect for privacy is an indicator that gives an estimation of the effectiveness of the processes for protecting consumer privacy. Customer satisfaction defines whether company products and services meet the customer expectations.

2.2 Blockchain technology in SSCM

This section explores the potential benefits and challenge of blockchain technology in solving the problems of sustainability measurement in supply chains. Thus, the current applications of blockchain in SSCM literature are analyzed.

Blockchain adoption in sustainable supply chains is a brand-new research area and it’s gaining momentum. Blockchain, from a sustainability standpoint, has the power to transform supply chain management (Manupati et al., 2020). Table 3 displays the main academic contributions of blockchain-based sustainable supply chain literature.

Table 3. Literature on Blockchain in Sustainable Supply Chain Management

Stream	Summary	Focus	Empirical Content-Methodology	Source
Blockchain in fulfilling supply chain objectives	Presented a theoretical framework from multiple case studies of how blockchain can help companies achieve key supply chain objectives	Benefits	Case study	(Kshetri, 2018)
Uses of blockchain in green supply chain	Identified potential uses of blockchain in green supply chain management for environmental sustainability.	Benefits	Conceptual	(Kouhizadeh & Sarkis, 2018)
Blockchain adoption barriers	Examined the barriers of blockchain adoption in supply chain networks in four levels: inter-organizational, intra-organizational, system-related and external barriers.	Adoption	Conceptual-review	(Saberi et al., 2019)
Success factors of blockchain adoption	Explored the critical success factors of blockchain development for supply chain sustainability.	Adoption	Experts' opinion-PCA, Fuzzy-DEMATEL	(Yadav & Singh, 2020)
Use of blockchain for supply chain sustainability	Analyzed the use of blockchain technology and Industry 4.0 for achieving sustainability in supply chains.	Benefits	Conceptual-review	(Esmaeilian et al., 2020)
Blockchain architecture for social sustainability	Proposed a system architecture using blockchain, IoT and big data analytics to track social sustainability in supply chains.	Benefits	Conceptual	(Venkatesh et al., 2020)
Blockchain framework for LCA	Developed a framework for blockchain-based life cycle assessment where smart sensors are deployed for monitoring the various phases of a product's entire lifecycle.	Benefits	Conceptual	(Zhang et al., 2020)
Blockchain technology adoption for LCA	Invesitgated the adoption of blockchain for implementing life cycle assessment and achieving targeted sustainability goals.	Adoption	Case study	(Teh et al., 2020)
Blockchain architecture for zero-waste circular economy	Developed a blockchain-based system architecture for circular supply chain management in fast fashion industry.	Benefits	Conceptual	(Wang et al., 2020)
Success factors for blockchain-based supply chain traceability system	Identified bussiness requirements and critical success factors for implementing a blockchain-based supply chain traceability system.	Adoption, benefits and challenges	Conceptual-review	(Hastig & Sodhi, 2020)
Blockchain adoption barriers	Theoretically observed the barriers that hinder blockchain adoption when integrating sustainability in the supply chains.	Adoption	Experts' opinion-DEMATEL	(Kouhizadeh et al., 2021)
Blockchain applications in sustainable manufacturing	Reviewed the literature on the blockchain applications in sustainable manufacturing and supply chain management.	Adoption, benefits and challenges	Literature review	(Khanfar et al., 2021)
Understanding of Industry 4.0 and sustainability	Systematically reviewed the papers related to Industry 4.0 and sustainability.	Adoption, benefits and challenges	Conceptual-review	(Beltrami et al., 2021)
Solutions to blockchain adoption barriers	Provided possible solutions to the blockchain adoption barriers in sustainable supply chains by analyzing an Italian fashion company.	Adoption	Case study	(Caldarelli et al., 2021)

Blockchain as a tool for supply chain sustainability was first mentioned by Kshetri in 2018. The study used multiple real-world cases to prove that the supply chain management goals are being accomplished by adopting blockchain in supply chains. Sustainability was one of the main supply chain objectives alongside cost, quality, speed, dependability, risk reduction, and flexibility (Kshetri, 2018).

In one of the cases, the company Provenance uses blockchain and smart tags to prove social sustainability against fraud, human rights abuses, and illegal practices in the fishing industry in Indonesia. Blockchain makes it possible to verify social sustainability by using individual participants' validation and a digital tracking system to trace the origin of the products. Another case mentioned is Everledger company which uses blockchain to combat fraud and counterfeit goods. The organization focuses on luxury items such as diamonds and fine wine and produces digital certificates for items to validate their authenticity and provenance. The business built a database on the blockchain to guarantee the diamonds were sourced ethically from conflict-free areas (Kshetri, 2018).

2.2.1 Benefits of blockchain technology in SSCM

2.2.1.1 Transparency, traceability and trust

Transparency and traceability of blockchain hold businesses accountable for their supply chain practices related to human rights, fair and safe work environment. Validating that supply chain processes and products fulfill sustainability standards and certifications is a significant strategic and competitive advantage for companies (Grimm et al., 2016). Such as, a product purchased from ethical sources can boost customer confidence (Saberi et al., 2019). Transactions are secured by cryptography that enables supply chain participants to securely exchange, view, and validate information (Chen & Bellavitis, 2020). Because no business or individual has the authority to modify the data recorded on the blockchain, the participants are more confident in the information they obtain. (Francisco & Swanson, 2018).

Transparency exposes unsustainable behavior, forcing firms to adopt sustainable practices (Mol, 2015). It can also bring out the companies that employ sustainable practices. Retailers may demonstrate their commitment to sustainability to their customers by providing information regarding sustainability certificates and appropriate workplace conditions in immutable documents across the value chain (Venkatesh et al., 2020). These approaches for assessing sustainability performance can identify critical suppliers throughout the supply chain. By using blockchain, supplier past performance data can be analyzed to ease decision-making processes when choosing sustainable performance criteria (Kouhizadeh & Sarkis, 2018). It will be easier to differentiate between providers who employ environmentally friendly practices (Bai & Sarkis, 2020).

A systematic literature review is made on the blockchain applications in sustainable manufacturing and supply chain management (Khanfar et al., 2021). The researchers classified that with smart contracts, traceability, transparency, security, and real-time information sharing, blockchain technology can contribute to the sustainability performance of supply chains.

2.2.1.2 Autonomy

Smart contracts can be capable of autonomously tracking and controlling terms and regulatory policies on sustainability, as well as enforcing or governing necessary adjustments (Saberi et al., 2019). For example, smart contracts which are self-executing codes, can be used to check whether conditions related to sustainability measurement are met.

2.2.1.3 Real-time tracking

Blockchains could be linked to Global Positioning System (GPS) and radio frequency identification (RFID) tags for real-time tracking (Abeyratne & Monfared, 2016). Hence, every participant can monitor the status and location of the products and share the identical information within the system (Kim & Laskowski, 2017).

Teh et al. (2020) refer to the possibilities of blockchain adoption in companies' sustainability strategies, especially in life cycle assessment (LCA) processes to overcome the limitations rooted in LCA, such as data integrity, traceability, and transparency of various stakeholders along the value chain. Zhang et al. (2020) present an application framework for blockchain-based life cycle assessment applications where smart sensors are deployed for monitoring energy, water, and other material consumption at different stages of a product's life cycle. The study states that LCA can be conducted utilizing real product information instead of predicted values employed in existing LCA, thanks to blockchain technology. Another study describes a system design that employs blockchain, IoT, and big data analytics to track the social sustainability of supply chains (Venkatesh et al., 2020). In system design, social sustainability is monitored with wearable technologies like smart bracelets. Employees are obligated to wear smart bracelets and shoes to collect their physiological data. Furthermore, cameras and sensors are used to observe workplace conditions like room temperature, humidity, noise pollution, etc. The data recorded on the blockchain can later assist in the certification of social sustainability (Venkatesh et al., 2020). However, physiological data collection can have adverse effects on employee psychology. It may trigger feelings of discomfort and distrust from being closely monitored while working (Venkatesh et al., 2020).

According to Esmaeilian et al. (2020), blockchain has the potential to be used in driving green behavior, increasing product visibility across the lifetime, boosting operations and system efficiency, and enhancing sustainability reporting.

2.2.1.4 Operations and system efficiency

The possible uses of blockchain in environmental supply chain management for environmental sustainability were identified by Kouhizadeh and Sarkis in 2018. The study claims that of all technologies, blockchain has a profound importance for supply chain sustainability. It mentions the possible uses of blockchain in a wide range of supply chain stages from vendor selection and supplier development, tracing the quality of materials produced, energy management, and monitoring the environmental impacts of logistics. This study also discusses circular economy, innovative and traceable packaging, carbon trading, and minimizing waste using smart contracts. These innovations can be maintained with blockchain with its secure, permanent, transparent, verified system.

Lim et al., (2021) suggests that research based on blockchain and sustainable supply chains are inadequate. Social and environmental dimensions are not comprehensively taken into consideration. On a social level, the literature mostly mentions product safety. Only Venkatesh et al. (2020), considers workplace conditions and work health and safety. In the case of environmental sustainability, the majority of the existing research emphases on reducing carbon emission and does not consider energy efficiency, waste management or greenhouse gas emission (Lim et al, 2021). In both aspects, there is a need for in-depth improvement of the sustainability metrics. Furthermore, the paper refers to the lack of quantitative research that presents a systematic model for sustainable supply chain performance in blockchain context. Hence, this thesis aims to fill this gap of a blockchain application for sustainability performance measurement in supply chains.

2.2.2 Challenges of blockchain technology in SSCM

The identification of challenges and barriers is the first step in successfully implementing blockchain technology to track sustainable practices and manage supply chain operations (Saberi et al., 2019).

2.2.2.1 Immaturity

According to Saberi et al. (2019), many technological challenges of blockchain adoption originate from blockchain technology's immaturity. Due to immaturity, scalability, latency and interoperability issues arise (Swan, 2015). Blockchain technology would struggle to handle a large number of transactions (Kouhizadeh et al., 2021).

2.2.2.2 Inadequate knowledge and expertise

Businesses that have little or no blockchain knowledge, and management assistance will fail to implement the technology. Executives are reluctant to adopt technology due to the absence of expertise (Saberi et al., 2019).

2.2.2.3 Problems with collaboration and communication

Collaboration among supply-chain stakeholders is necessary to make blockchain integration work in supply chains. The unwillingness of some partners to disclose information may restrict the technology implementation and impede its deployment (Kouhizadeh et al., 2021).

2.2.2.4 Risk of human error and immutability

The accuracy of the information entered to the blockchain may not reflect the reality (Hastig & Sodhi, 2020). The research states that data falsification is possible with the blockchain in the same way that it is possible to fake data by distorting the facts while utilizing centralized systems. Furthermore, any incorrect information placed into the system would be permanently displayed and could only be changed by inserting new information into the blockchain (Kouhizadeh et al., 2021).

2.2.2.5 High energy consumption

The high processing power required for PoW consensus systems necessitates the consumption of hundreds of megawatts of energy (Kouhizadeh et al., 2021). High energy use also results in higher carbon emissions that are harmful to the environment.

2.2.2.6 Lack of standardization

Lack of standards hinders interoperability. A effective supply chain tracking system necessitates the timely gathering of standardized data, as well as the storage and analysis of the measurements (Hastig & Sodhi, 2020).

2.2.2.7 Lack of governmental policies

In the global value chain context, blockchain technology would have to comply with a variety of laws, regulations of various countries, along with agreement limits on data privacy and management (Hastig & Sodhi, 2020). Existing rules are inadequate to govern cryptographic operations, and a thorough examination of the present legislative framework is required (Bai & Sarkis, 2020).

CHAPTER 3

BACKGROUND ON BLOCKCHAIN TECHNOLOGY

The following chapter presents an overview of blockchain technology. The blockchain features and technical aspects of the technology are briefly explained.

In 2008, after the crash of the global financial crisis, a pseudonymous individual or individuals known as Satoshi Nakamoto developed a novel protocol for a peer-to-peer electronic cash system based on the cryptocurrency Bitcoin (Teh et al., 2020). Blockchain is the essential technology upon which the entire Bitcoin network is built. The fundamental aspects of blockchain technology are defined as "the database that is shared by all network nodes, secured through cryptography, continuously updated by miners, monitored by everyone, and owned and controlled by no one" (Swan, 2015, p. 1). A noteworthy property of the blockchain system is that it is peer-to-peer and decentralized. This refers to a collective environment where individuals communicate directly with each other without the need for an intermediary or a unit of control. The information is shared publicly among everyone and it is stored in the computers of users, also known as the nodes. Blockchain is composed of linked chain of blocks. “Each block is identified by its unique cryptographic hash, and it is linked with other blocks based on the hash of the previous block to form a cryptographically linked chain of blocks” (Bahga & Madisetti, 2016, p. 535). Various computational algorithms are deployed to prevent double-spending and modification of previous transactions. When a transaction is recorded to the blockchain, it cannot be changed, making it an tamper-proof record of previous actions (Seebacher & Schüritz, 2017). Transactions can only be added and cannot be removed (Iansiti & Lakhani, 2017). Thus, blockchain is a distributed network with a growing collection of irreversible records.

Trust is maintained among the network due to the approval or mining process where each new transaction is validated by the entire network of miners before being added to a blockchain (Abeyratne & Monfared, 2016). Improvements to the system are made when reaching a consensus and can be realized when accepted by more than half of the individuals within the system. The most well-known consensus algorithms are Proof-of-Work (PoW) and Proof-of-Stake (PoS). In PoW algorithm, miners solve challenging mathematical problems to add new blocks to the original blockchain. There is fierce competition between miners, whoever decrypts the computational problem first gets rewarded with coins. Yet, the procedure of cracking complex problems requires a huge amount of computational power which consumes a lot of energy (Hooda, 2019). Another common algorithm is PoS. PoS does not demand problem-solving. Instead of miners, stakers do the verification processes. Stakers are determined by the number of coins they hold. They are limited to mining a proportion of blocks equivalent to their ownership of stake (Yaga et al., 2019).

The Economist identifies blockchain technology as “the great chain of being sure about things.” (The Economist, 2015). It's a platform where everyone can find out what's true—at least in terms of structured recorded information (Tapscott & Tapscott, 2016). The digital ledger of economic transactions can be programmed to record anything with value that can be expressed in code: birth and death certificates, property deeds and titles, educational degrees, bank accounts, votes, food provenance, etc (Tapscott & Tapscott, 2016).

3.1 Blockchain features

3.1.1 Decentralization

Blockchain technology enables transactions to occur without the need for any central database, organization, or authority (Swan, 2015). The information is stored in a secure and decentralized manner in the peer-to-peer network. Every network participant has the identical version of records that are constantly renewed with new data (Swan, 2015). Since no central authority is needed to record transactions among peers inside the network, blockchain has the ability to greatly cut server costs while also alleviating any lack of functionality via the central database (Zheng et al., 2018). A central system is more susceptible to cyber attacks, malfunction, or failure (Tian, 2016). On the other hand, decentralization enhances data quality and reliability by making transaction records available via the distributed ledger (Crosby et al., 2016). The centralized, decentralized and distributed networks are illustrated in Figure 3.

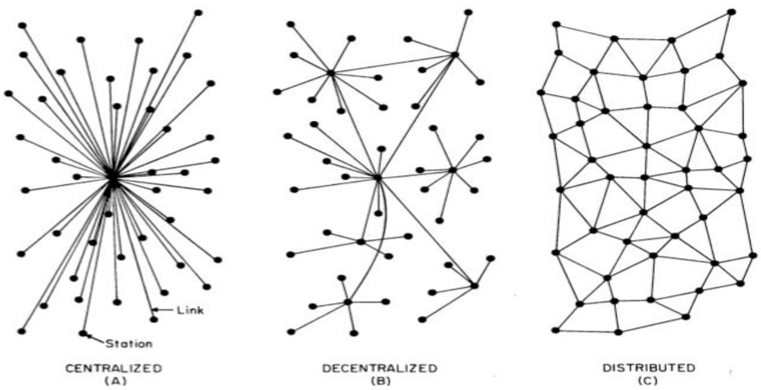


Figure 3. Centralized, decentralized, and distributed networks
[Baran, 1964]

3.1.2 Security

Blockchain technology creates a secure platform through cryptography (Tapscott & Tapscott, 2016). Cryptography is used to record and verify every transaction on the blockchain. Because the data is exchanged and regularly checked by a network of trusted computers, the distributed structure makes it incredibly difficult for hackers to attack (Atzori, 2015). As a result, the blockchain system is resistant to single points of failure; even if one participant is hacked or fails, the network stays intact (Mougayar, 2016).

3.1.3 Immutability

The information on the blockchain is immutable. Transactions cannot be modified or adulterated until more than 50% of the network nodes are managed at the same time by a certain user (Lin & Liao, 2017). Because no single entity controls the transaction, blockchain's decentralization promotes the sharing of the same information across the whole network.

3.1.4 Auditability

When a transaction is validated and added to the blockchain, it is broadcasted to the network. The whole system functions as a transparent platform via nodes that can track the origin of each record (Tian, 2016). All transactions are signed using a private key that only one individual possesses. Thus, transactions can be connected directly to the person who performed the transaction, enabling accountability. Because every transaction is recorded and authenticated with a timestamp, earlier records in the decentralized network can be easily traced and verified. Members of the network can see the entire history of transactions, allowing for auditability and traceability (Underwood, 2016).

3.1.5 Smart contracts

Smart contracts are computer codes that incorporate contract terms and agreements (Kouhizadeh & Sarkis, 2018). The transactions are conducted automatically under the negotiated terms and authenticated against agreed conditions. In contrast to traditional contracts, smart contracts can limit the participation of a middleman to a bare minimum, potentially leading to increased productivity and cost savings through company activities (Kouhizadeh & Sarkis, 2018). Smart contracts inspect established criteria, such as rules and fines decided upon by network participants, and take the required action as a result of those conditions (Kouhizadeh & Sarkis, 2018).

3.1.6 Anonymity

The blockchain system does not require users to disclose their personal information to download and use the network (Tapscott & Tapscott, 2016). Furthermore, personal information is not maintained in a centralized database and therefore is not controlled by any third party. Each network user own a public and a private key, which are used to display a person's identity on the network. Participants have total control over their level of privacy, they can stay anonymous or prove their identity by revealing their public key to others (Mougayar, 2016).

3.2 Technical aspects

3.2.1 Block formation

Blocks are data structures that contain information. Each block in a blockchain contains several kinds of information. First, a block contains the hash of all the content that is stored. Hashing is a process in which tangible and intangible resources (such as raw materials and ownership) are turned into digital codes that can subsequently be recorded, traced, and traded on the blockchain (Franciso & Swanson, 2018). A hashing function is deterministic in the sense that it always produces the same result when given the same input. A small alteration in the hashing function's input results in a vastly different output (Yaga et al., 2019). This hash function helps in ensuring that a certain piece of information has not been altered or updated. Second, each block includes the hash value of the previous block. This results in the formation of an interconnected chain of blocks. In a block, all the transactions of that block are hashed together with the previous block hash and the nonce (Figure 4). A nonce is a number that is iteratively incremented by network miners to solve the PoW hash puzzle. A Merkle Tree method, which involves more complicated hashing, is also employed in each block to strengthen the security of the blockchain. Third, each block carries a timestamp, which guarantees that a given piece of information exists at a specific moment, which makes transactions easier to track and keep the information safe (Yaga et al., 2019).

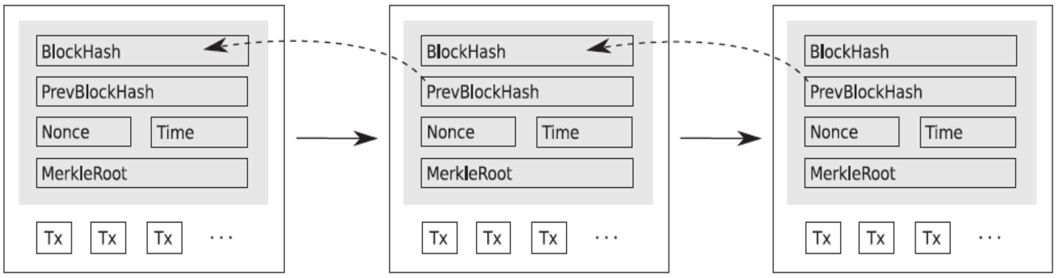


Figure 4. Simplified representation of blockchain
[Tschorsch & Scheuermann, 2016]

3.2.2 Transactions

Blockchain employs asymmetric-key cryptography to guarantee the veracity and validity of transactions (Yaga et al., 2019). Each user in the network has a wallet that contains a public and a private key that enables them to sign transactions in the blockchain. Users are identified in the network with these key pairs. Only the user has access to their private key, in contrast, the public key is shared across the network.

3.2.3 Mining

The blockchain network is made up of a network of users known as nodes. Every node has a replica of the blockchain ledger, which is a record of bitcoin transactions between users. Miners are nodes that validate transactions and compete to create blocks. The process of confirming and producing a block includes solving a complex mathematical problem that requires a significant amount of processing power, as well as validation by other nodes. Proof-of-work refers to the consensus system set up to create blocks and reach an agreement on the validity of new blocks. If their block is chosen to be added to the blockchain, miners are rewarded with bitcoin for their efforts in keeping the network secure. Finding a block hash with a specific number of leading zeroes, given by the difficulty level variable nonce on the block header. When a block is validated and the consensus is obtained, it is spread around the network and recorded on the ledger.

CHAPTER 4

METHODOLOGY

This chapter explains the research methodologies applied to address the established research questions. The methodologies applied in the thesis are systematic literature review and design science research.

4.1 Systematic literature review

A systematic literature review methodology has been chosen to gain a deeper knowledge of the existing studies related to environmental and social sustainability indicators in the supply chain. The SLR is carried out following Kitchenham's criteria (2004). According to Kitchenham, a systematic review includes three stages: planning, conducting the review and reporting the results. The SLR steps are illustrated in Figure 5 in detail.

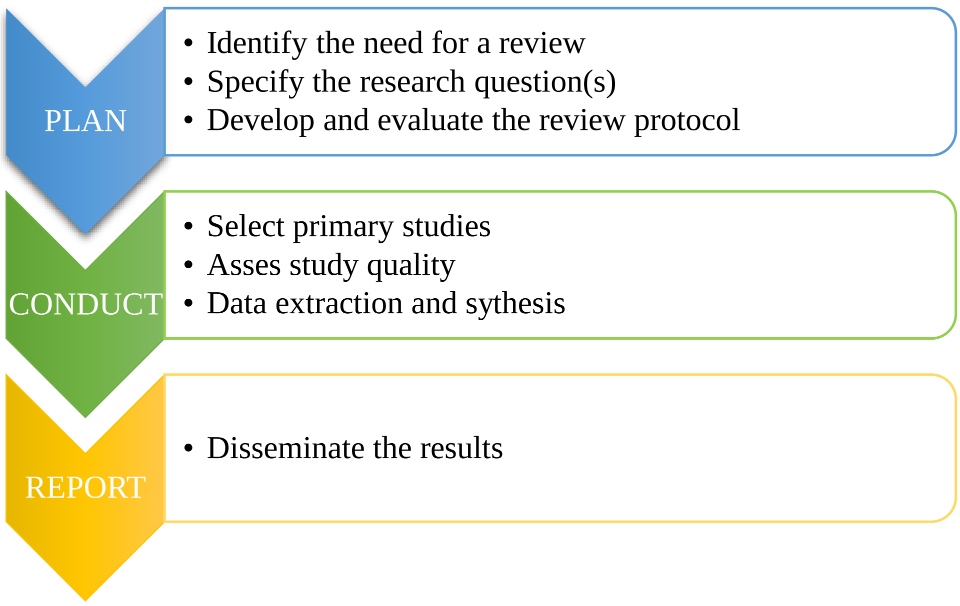


Figure 5. Systematic Literature Review Stages
[Adapted from Kitchenham (2004)]

4.1.1 Planning

As the first stage of a SLR, it is required to acknowledge the necessity of a review. SLR can be done to summarize the existing literature, identify gaps and provide a background to appropriately position new research (Kitchenham, 2004). After explaining the need for a review, the research questions are stated in Chapter 1. Subsequently, the development of a review protocol is applied that includes selection criteria, quality evaluation checklists, data extraction approach, and synthesis of the extracted data. Afterwards, the protocol is evaluated whether search words are properly acquired from the research questions and whether the data extracted and analyzed is suitable to answer the questions.

4.1.2 Conducting the review

The SLR aims to discover a significant number of primary papers related to the research question using an impartial search technique (Kitchenham, 2004). In the search strategy, the terms are determined by the research questions and their validity is checked with already known primary studies. The study selection should include papers that give concrete proof on the research problem. The criteria for inclusion and exclusion are dependent on issues of language, journal, research design, subjects, methods, etc (Kitchenham, 2004). The selection criterias applied in the review are mentioned in Section 2.1.2. Consequently, data obtained from the primary studies are extracted. In the data extraction process, multiple articles with the same data are avoided due to bias. Next, in the data synthesis part the results are summarized and are tabulated consistently with research questions.

In this thesis, initially, the methods to measure supply chain sustainability are analyzed. As a result of the analysis, it is found that the current sustainability assessment tools do not consider all stakeholders when measuring supply chain sustainability and do not include all sustainability aspects. Upon this finding, a systematic literature review is done to identify the environmental and social sustainability indicators. The indicators in the literature were mostly qualitative and there was a need for quantitative indicators to be able to measure sustainability. Thus, a quantitative sustainability assessment framework was created to be utilized in the sustainability measurement of all supply chain actors. The frameworks can be found in Appendix A- C.

4.1.3 Reporting the review

In the reporting part of the SLR, it is crucial to effectively communicate the research findings (Kitchenham, 2004). The conducted systematic review is portrayed to an audience in the form of a thesis.

4.2 Design science research

In this thesis, design science is applied as the second methodology. The intersection of behavioral science and design science in the realm of information systems is known as design science research (March & Storey, 2008). DSR is a problem-solving technique that focuses on the design and building of artifacts that can be used to analyze, develop, implement, and use information systems effectively and efficiently (Hevner et al., 2004). To conduct an effective DSR, the seven guiding principles of design science research proposed by Hevner et al. (2004) are adopted. The summary of the principles is listed in Figure 6.

Guideline	Description
Guideline 1: Design as an Artifact	Design science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation
Guideline 2: Problem relevance	The objective of design science research is to develop technology-based solutions to important and relevant business problems
Guideline 3: Design evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods
Guideline 4: Research contributions	Effective design science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies
Guideline 5: Research rigor	Design science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact
Guideline 6: Design as a search process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment
Guideline 7: Communication of research	Design science research must be presented effectively to both technology-oriented and management-oriented audiences

Figure 6. Design Science Research Guidelines
[Hevner & Chatterjee, 2010]

4.2.1 Design as an artifact

In this study, a blockchain-based DSS is developed to measure the environmental and social performance of supply chains. The artifacts employed in this research are as follows. The information system is designed to gather the data from the supply chain actors, calculate their environmental and social sustainability assessments and transfer them to the relevant stakeholders. At the same time, the blockchain-based system can be used to prove the origin of the products, track and trace the product journey throughout the supply chain, and measure the product life cycle inventory.

4.2.2 Problem relevance

The goal of information systems research is to gain understanding and insight that will lead to the creation of technology-based solutions to unresolved and significant organizational challenges (Hevner et al., 2004). This thesis aims to investigate the potential of blockchain technology as a solution to sustainability problems in global value chains. The relevant unsolved problems are further stated in Chapter 1.

4.2.3 Design evaluation

As mentioned in the guideline, evaluation of the an artifact is an important part of DSR. To evaluate the effectiveness, efficiency, and flexibility of the system, a simulation and an interview with a professional expert are conducted.

4.2.4 Research contributions

The clear contribution of this research is artifact of the blockchain-based DSS that measures the sustainability performance of the supply chain. Also, the knowledge base is extended with the quantitative sustainability assessment framework.

4.2.5 Research rigor

Rigor is obtained through the successful utilization of knowledge base and research techniques in both design-science and behavioral-science research (Hevner et al., 2004). The rigorous methods applied in this research are systematic literature review and design science research.

4.2.6 Design as a search process

In the design as a search process part, the business process needs and the features offered by leading supply chain management systems has been examined in detail. Moreover, the system is refined iteratively with feedback obtained from a professional.

4.2.7 Communication of research

This research is aimed at both technological and management audiences. It appeals to a technologically savvy audience through the use of blockchain technology and the creation of an information system. The managerial audience, on the other hand, will be more interested in the supply chain sustainability management aspect of this research.

CHAPTER 5

DEVELOPMENT OF THE BLOCKCHAIN-BASED DSS

This chapter provides an overview of the DSS developed to assist businesses in decision-making processes related to sustainability. The DSS architecture is defined. Subsequently, the development tools and languages used in implementing the blockchain system are explained. Later, the DSS sustainability model and blockchain database and smart contracts are elaborated. Finally, the system implementation is demonstrated with an application scenario and the screenshots of the user interface are presented.

5.1 DSS architecture

A DSS is composed of three components; a model base, a database, and a user interface. The model base component is a sustainability assessment model that calculates the environmental and social sustainability performance of the supply chain. It also does the life cycle inventory analysis of the product produced. The database is a blockchain database that stores the system inputs. The model runs on the user interface (UI) built on the React framework using JavaScript language. The UI allows users to run the sustainability model and presents the results in tables and charts.

The data flow of the DSS is provided in Figure 7. The user enters input data into the system. These can be the data for environmental and social sustainability, or life cycle inventory. The environmental and social dimensions are taken into account as they are less considered compared to the economic dimension when measuring organizational sustainability. When the data is entered, the user runs the sustainability model. Once the model is run, the data entered is uploaded to the blockchain database. The sustainability model retrieves the data from the blockchain database to calculate sustainability assessments and reports. After this step, the user can view the sustainability assessments in tables and charts.

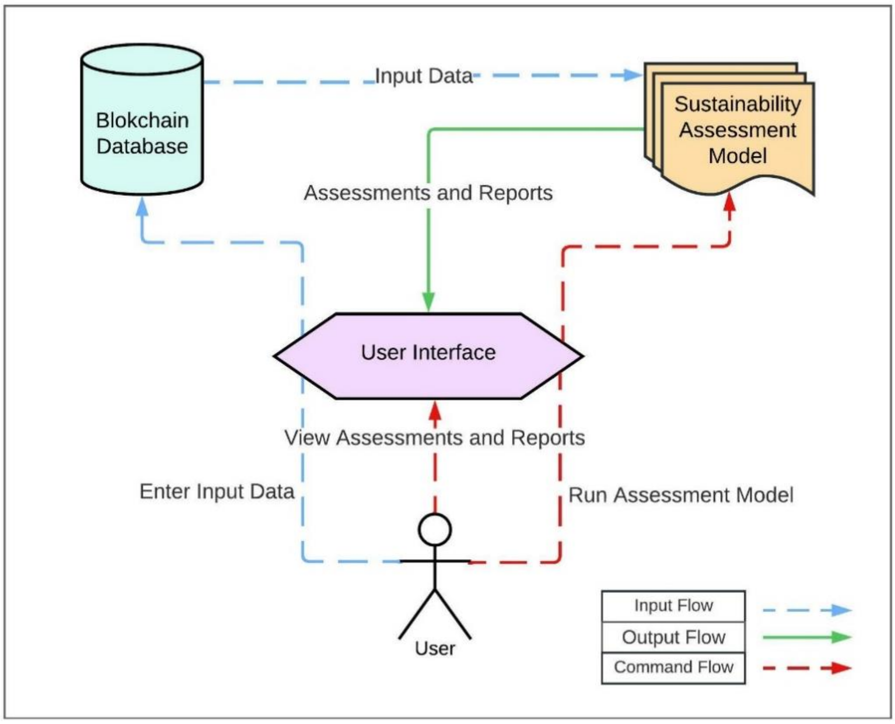


Figure 7. Information flow in the DSS

5.2 System development tools

The Ethereum blockchain framework is used in the implementation of the blockchain-based sustainability measurement system. The Ethereum blockchain is chosen for its smart contract technology that enables programmed code to automatically execute and its user-friendly environment that allows users to access data and interact with smart contracts. Ethereum Virtual Machine allows developers to create decentralized applications. Solidity coding language is used to compile smart contracts and communicate with the Ethereum blockchain. Figure 8 shows the application architecture, the development software and libraries used in the development and implementation stages.

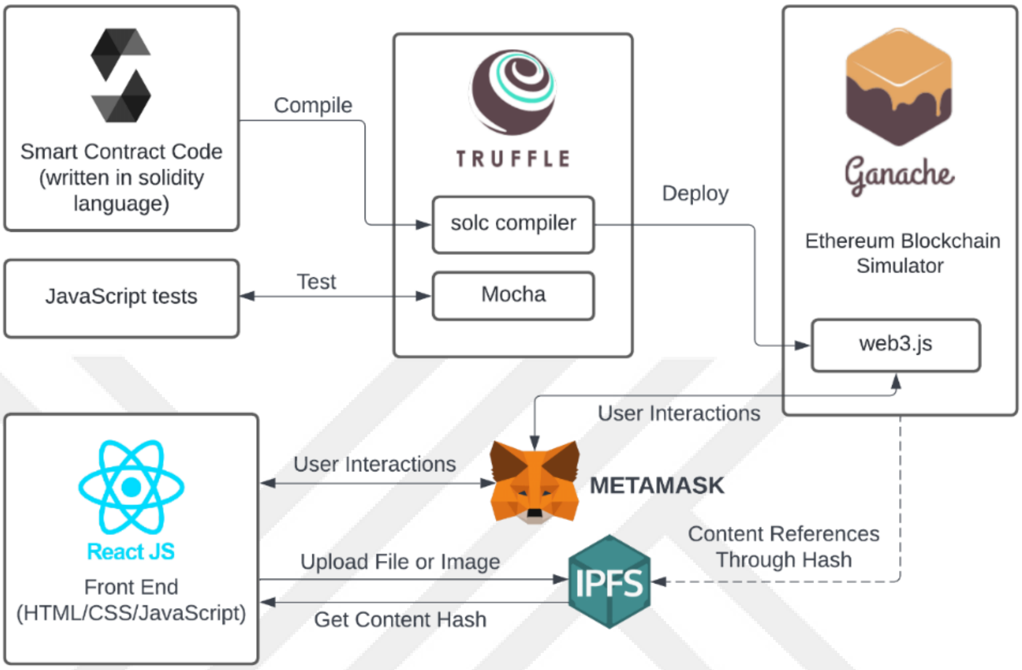


Figure 8. System architecture

Truffle is a smart contract development and testing framework for Ethereum. The smart contracts are compiled, tested, and deployed to the local blockchain with the Truffle framework. Truffle uses Mocha, a JavaScript testing framework, and the Chai assertion library to validate the correct execution of smart contracts. Ganache is the local blockchain simulator for the development of Ethereum applications. The local chain allows developers to develop, deploy, and test dApps and smart contracts in a safe and deterministic environment. Web3.js is the collection of JavaScript libraries that connects remote or local Ethereum networks with smart contracts. The system user interface is built with React which is a front-end JavaScript library. On the back-end, the Node.js JavaScript runtime environment is used. Metamask is a cryptocurrency wallet that connects to the blockchain network. It allows users to make transactions and interact with smart contracts via the browser extension. It essentially acts as a bridge between the Ethereum blockchain and the browser. InterPlanetray File System (IPFS) is utilized for storing large amounts of data such as images, videos, and files on the blockchain. It is a peer-to-peer storage network. When an image is uploaded to the IPFS a hash of that image is returned. The hash of the image is stored in the blockchain and the image content can be viewed anytime through its hash value.

5.3 Sustainability measurement model

A blockchain-based quantitative sustainability measurement model is created for decision-making processes. The model aims to assess the environmental and social sustainability performance of the supply chain actors. These actors can be suppliers, manufacturers, logistic companies, and focal companies such as retailers, wholesalers and distributors. Furthermore, the framework measures the environmental impact of the manufactured product with life cycle inventory (LCI) analysis. LCI is a methodology for measuring the consumption of resources, the amounts of waste flow, and emissions generated by or related to a product's life cycle (Rebitzer et al., 2004). It calculates environmental impact per unit of production. The provided measurement frameworks are universal and can be applied to all industries. It consists of 23 environmental, 25 social sustainability and 16 LCI indicators. The description and the source of each indicator can be found in Table 1 and Table 2 of Chapter 2. The proposed novel set of quantitative environmental and social sustainability and LCI indicators are given in Appendix A, B, and C respectively.

Due to the different time intervals of the indicators, quantitative measures are divided into monthly KPIs and annual KPIs. Monthly KPIs are input measures that need to be entered each month or whenever the input values change. Annual KPIs are input measures that need to be entered each year or whenever the input values change. When the monthly and annual input measures are entered into the system, the system calculates quantitative sustainability indicators according to the formulas in the sustainability measurement framework. The mathematical formulas and assessment criteria can be found in Appendix A, B, and C under the title input description. The mathematical formulas are gathered from the various papers in literature. Within the information system, all the data in the input description is collected from the suppliers and the focal companies. Focal companies can use these assessments and charts to analyze the environmental and social impacts of their supply chain and make decisions accordingly. They can also use it when selecting suitable suppliers.

5.4 Blockchain database and smart contracts

The database that is used in the DSS is a local blockchain. The information collected from the system is stored to the blockchain when the smart contract functions are executed. Moreover, the data is classified according to the data structures written in the smart contract codes.

There are two smart contracts deployed on the local blockchain. The Origin smart contract allows product, order, and shipment details to be recorded (Figure 9). It consists of the following functions that can be called once the contract has been deployed to the blockchain (see Appendix D for the complete smart contract code).

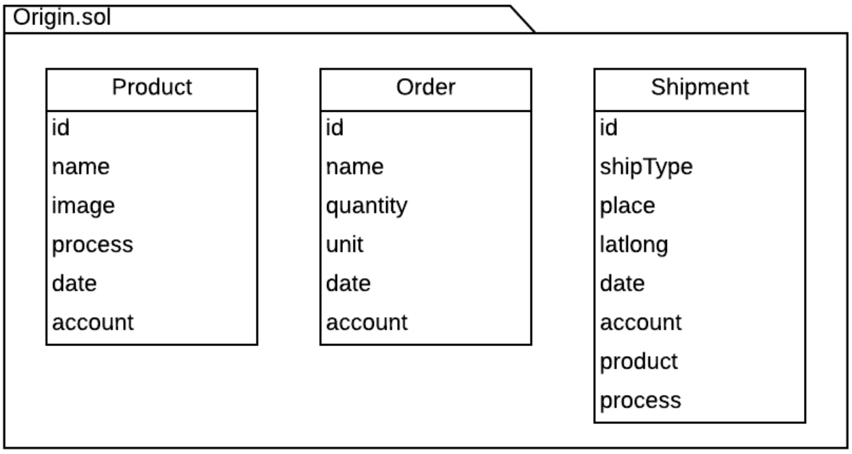


Figure 9. Origin smart contract data structures

addProduct function allows the company to record the product name, image, and production processes to the blockchain. The image added is uploaded to InterPlanetary File System (IPFS) and the hash of the image is stored on the blockchain.

addOrder function enables the company to record orders to the blockchain. The user chooses the product to order and enters the desired quantity and unit.

addShipment function allows suppliers or manufacturers to send or receive order shipments at each production step. It gets values of latitude, longitude, address, date and time added, product production process information, and whether the shipment is sent or received. The product shipment information determines the origin of the product. It enables the tracking of shipped goods throughout the supply chain.

The Assessment smart contract records environmental and social sustainability assessments of supply chain actors to the blockchain (Figure 10). It also stores data on the life cycle inventory of products in each production stage. It consists of the following functions that can be called once the contract has been deployed to the blockchain (see Appendix D for the complete smart contract code).

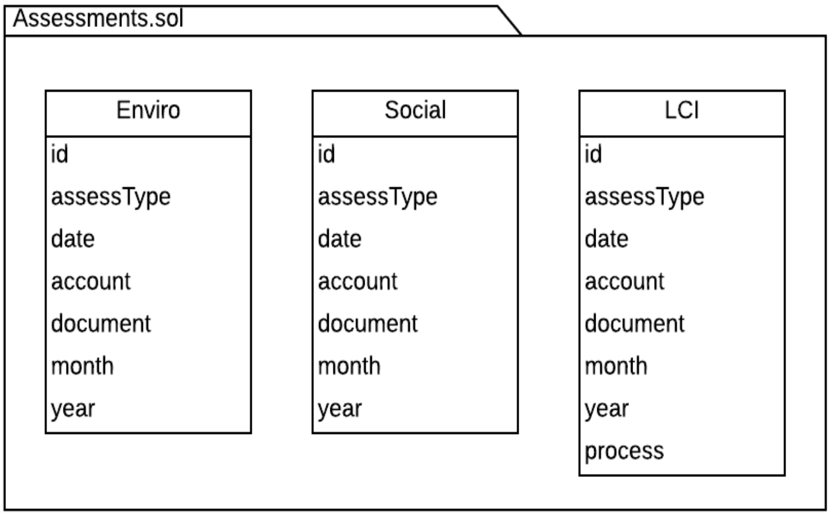


Figure 10. Assessments smart contract data structures

addEnviro and addSocial functions store assessment form documents that are filled out by suppliers or the focal company. It also records the month and year of the assessment, user account, and the date and time of the record.

addLCI function stores a life cycle inventory form document that is filled out by suppliers or the focal company. Additionally, it stores the production process, the month and year of the LCI and user account, and the date and time of the record.

5.5 System implementation

An application scenario is created to test the effectiveness of the blockchain-based system in measuring supply chain sustainability.

5.5.1 Application scenario

In the scenario, the journey of a product is tracked as it travels through the supply chain, and the environmental and social sustainability of the supply chain is measured. The hypothetical product tracked is an organic cotton t-shirt produced in

Turkey, a leading country in organic cotton production. The illustration of organic cotton production processes can be seen in Figure 11.

Figure 11. Supply chain processes of an organic cotton t-shirt

The first production process is cotton harvest. It begins with planting the cotton seeds. The cotton seeds are fed with water and organic fertilizers and are grown into cotton plants. The second process is yarn manufacturing. Once the cotton balls are collected by the farmers, they are transferred directly to the ginning factory by a truck. In the factory, the ginning machine separates cotton fibers from the seedpods removing any dirt, stems, and leaves. The cotton balls separated from the seeds are passed through a carding machine to become yarns. In the third process, the yarns are transferred to another factory to be knitted into cotton fabric. Next, the cotton fabric is dyed with dyes and sent to the garment factory. The garment workers cut and sew the dyed fabric according to the design using sewing machines. Once the garment is finished it is transferred to storage. The business that sells organic t-shirts is an online merchandiser.

The DSS work flow is demonstrated as follows (Figure 12). The users of the system are focal companies, suppliers and customers. First, users connect to the system with their blockchain addresses via Metamask.

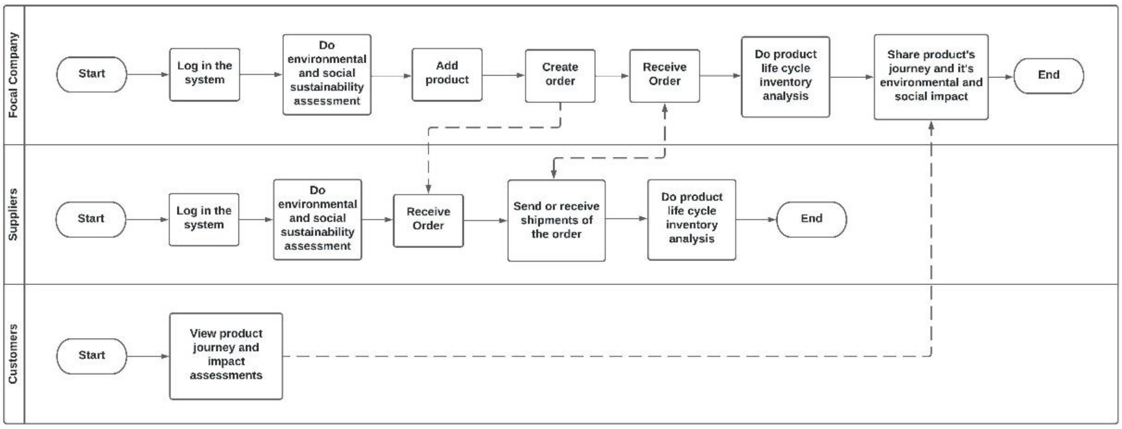


Figure 12. The DSS work flow

In the assessments page (Figure 13), the focal company and its suppliers do the environmental, social assessments to measure their monthly or annual sustainability performance. The information collected for the environmental and social assessment can be found in the Appendix A and B under the title input description.

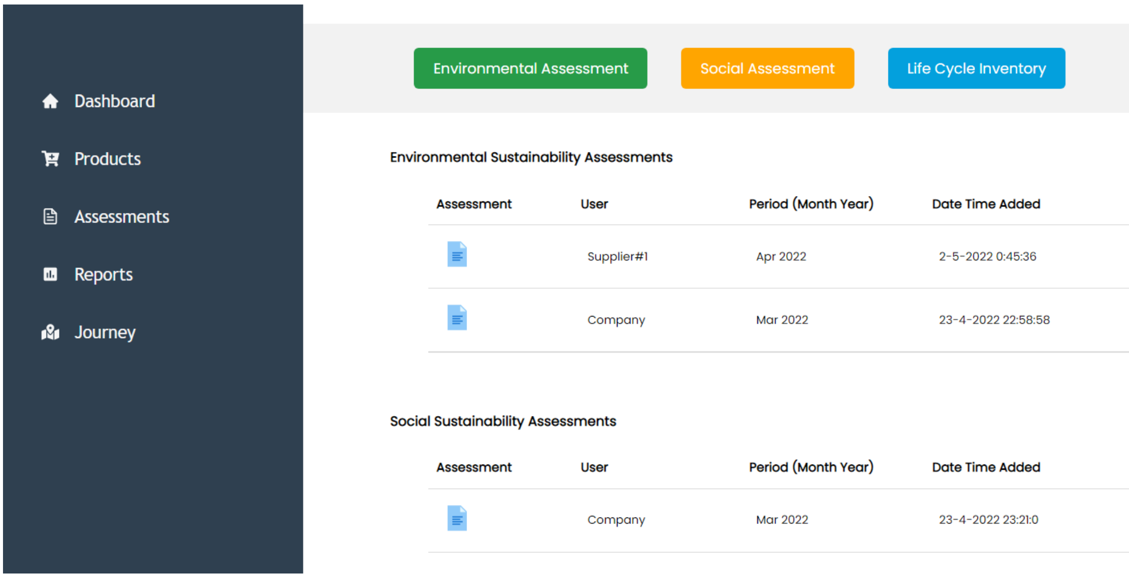
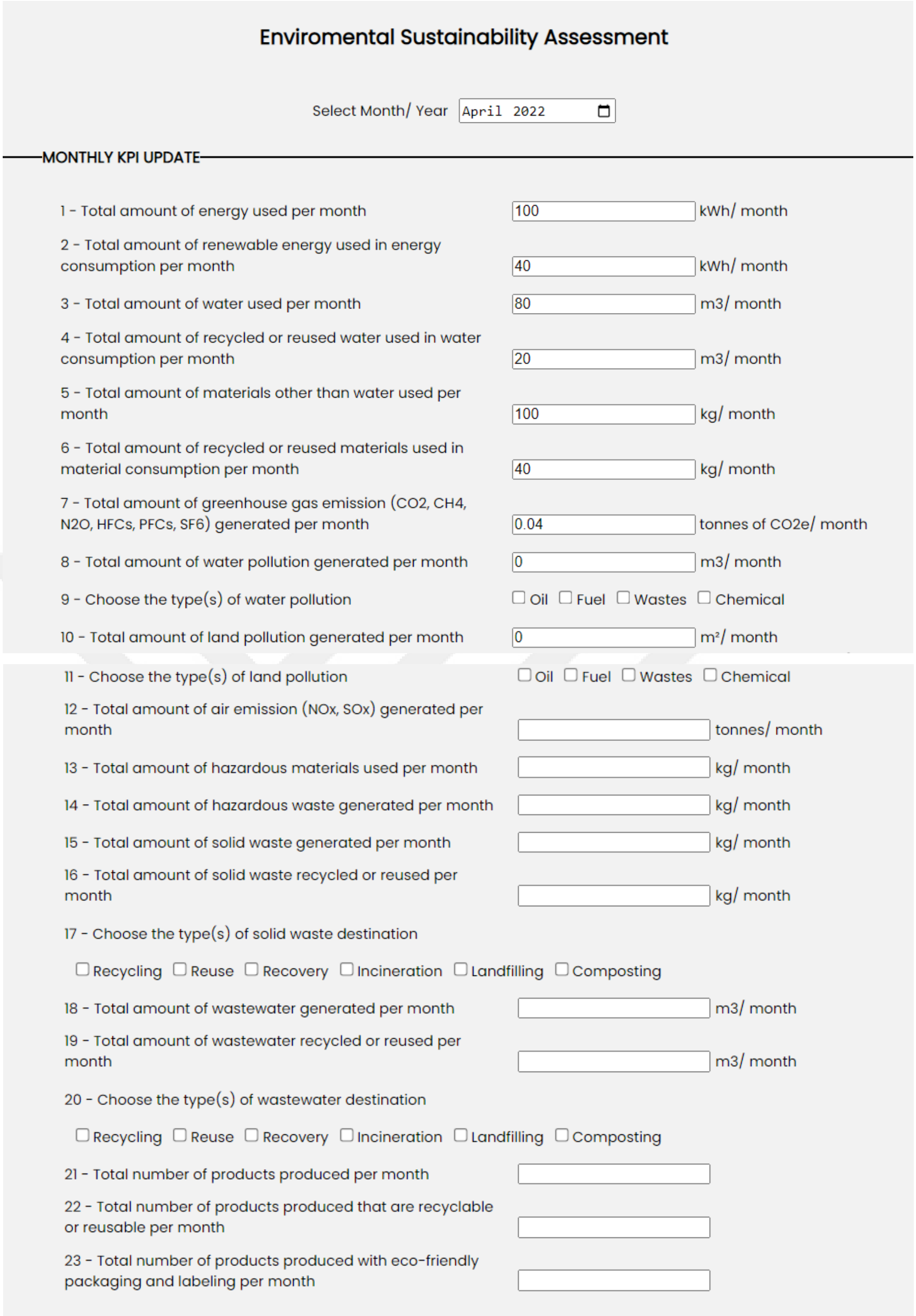


Figure 13. Assessments page

In order to do an assessment, relevant information must be entered into the assessment form (Figure 14).



Enviromental Sustainability Assessment

Select Month/ Year April 2022

MONTHLY KPI UPDATE

1 - Total amount of energy used per month	100	kWh/ month
2 - Total amount of renewable energy used in energy consumption per month	40	kWh/ month
3 - Total amount of water used per month	80	m3/ month
4 - Total amount of recycled or reused water used in water consumption per month	20	m3/ month
5 - Total amount of materials other than water used per month	100	kg/ month
6 - Total amount of recycled or reused materials used in material consumption per month	40	kg/ month
7 - Total amount of greenhouse gas emission (CO2, CH4, N2O, HFCs, PFCs, SF6) generated per month	0.04	tonnes of CO2e/ month
8 - Total amount of water pollution generated per month	0	m3/ month
9 - Choose the type(s) of water pollution	☐ Oil ☐ Fuel ☐ Wastes ☐ Chemical	
10 - Total amount of land pollution generated per month	0	m²/ month
11 - Choose the type(s) of land pollution	☐ Oil ☐ Fuel ☐ Wastes ☐ Chemical	
12 - Total amount of air emission (NOx, SOx) generated per month		tonnes/ month
13 - Total amount of hazardous materials used per month		kg/ month
14 - Total amount of hazardous waste generated per month		kg/ month
15 - Total amount of solid waste generated per month		kg/ month
16 - Total amount of solid waste recycled or reused per month		kg/ month
17 - Choose the type(s) of solid waste destination	☐ Recycling ☐ Reuse ☐ Recovery ☐ Incineration ☐ Landfilling ☐ Composting	
18 - Total amount of wastewater generated per month		m3/ month
19 - Total amount of wastewater recycled or reused per month		m3/ month
20 - Choose the type(s) of wastewater destination	☐ Recycling ☐ Reuse ☐ Recovery ☐ Incineration ☐ Landfilling ☐ Composting	
21 - Total number of products produced per month		
22 - Total number of products produced that are recyclable or reusable per month		
23 - Total number of products produced with eco-friendly packaging and labeling per month		

Figure 14. The focal company enters information into the environmental assessment form

After submitting the assessment form, the system automatically calculates sustainability indicators. The assessments can be viewed by clicking on the document icons in the assessments page (Figure 15 and 16).

Environmental Sustainability Assessments

Assessment	User	Period (Month Year)	Date Time Added
	Company	Apr 2022	3-5-2022 18:4:56

Figure 15. Environmental assessment is added to the system

Enviromental Sustainability Assessment for Company

For the period Apr 2022

Categories	Indicators	Measurements	Values	Units
	Energy Consumption	Amount of energy used per month	100	kWh/ month
	Energy Efficiency	Amount of energy reduced per month		kWh/ month
		Percentage of energy reduced per month		%
	Renewable Energy	Amount of renewable energy used per month	40	kWh/ month
		Percentage of renewable energy used per month	40	%
	Water Consumption	Amount of water used per month	80	m3/ month
	Recycled Or Reused Water	Amount of recycled or reused water used per month	20	m3/ month
		Percentage of recycled or reused water per month	25	%
Natural Resources	Material Consumption	Amount of materials other than water used per month	100	kg/ month
	Material Efficiency	Amount of materials reduced per month		kg/ month
		Percentage of materials reduced per month		%

Figure 16. Environmental sustainability assessment

Moreover, from the reports page, stakeholders can view reports related to their sustainability performance (Figure 17).

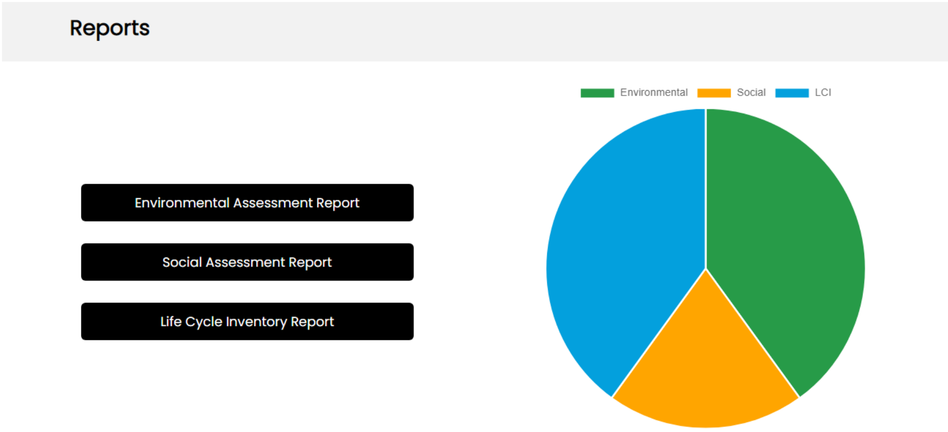


Figure 17. Reports page

The focal company or suppliers can display the environmental and social sustainability indicators with charts (Figure 18 and 19). In the charts, indicators are grouped according to similarities of their measurement units or their contexts. Also, in the chart section various sustainability assessments can be viewed at the same time or can be filtered by month or year. Thus, stakeholders can analyze and compare their past performances and evaluate their sustainability progress.

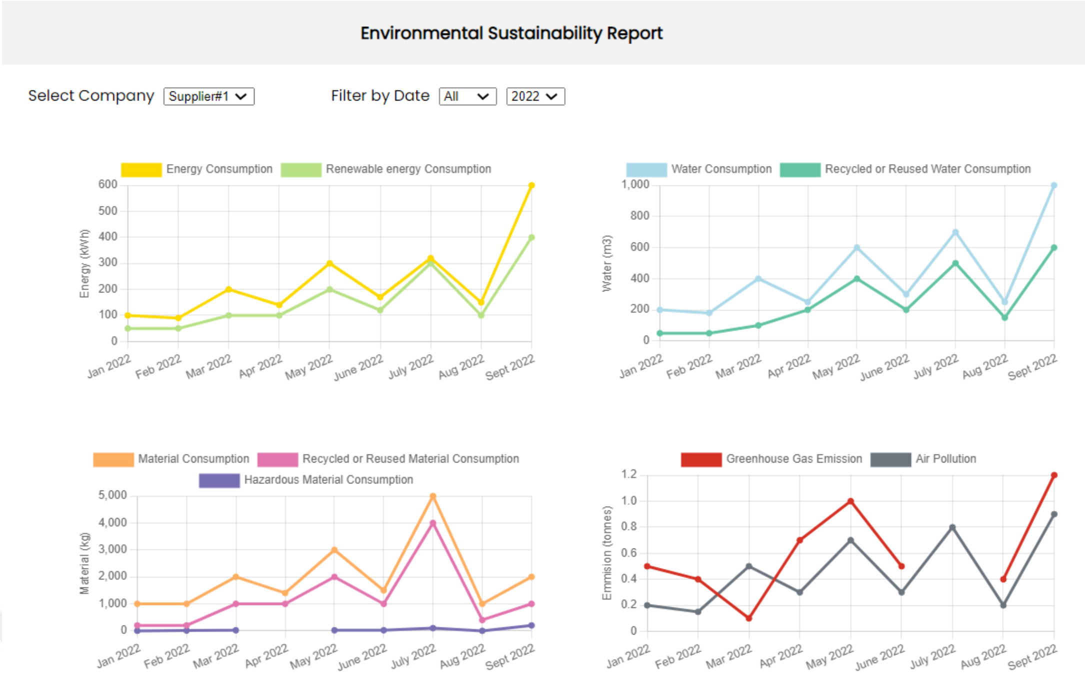


Figure 18. Environmental sustainability report

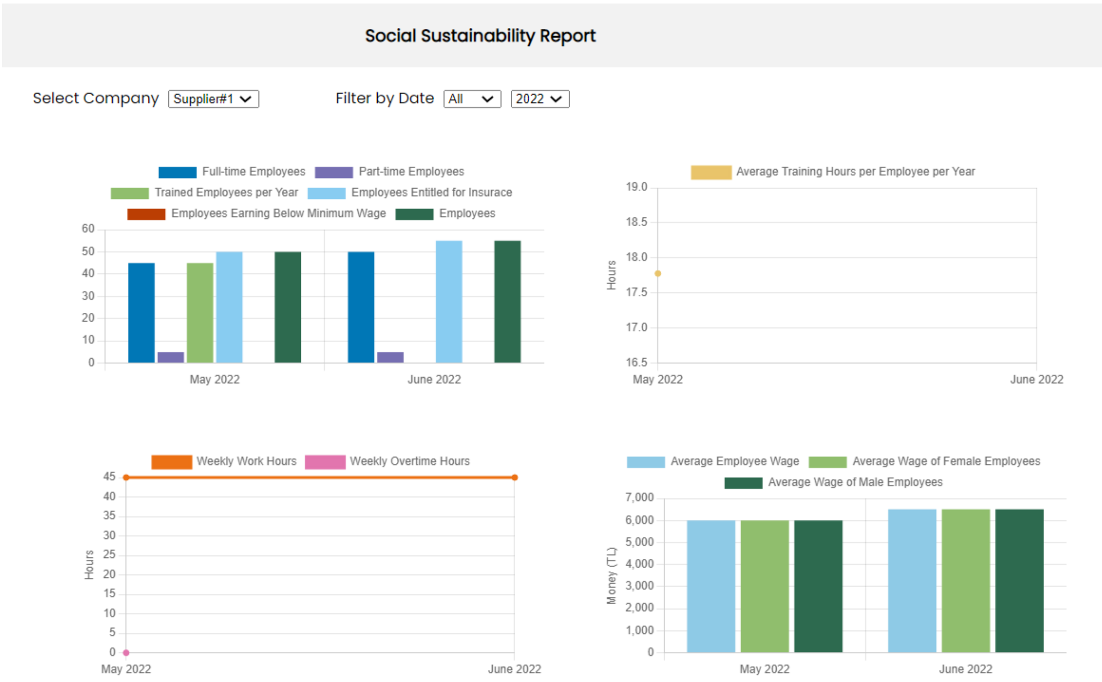


Figure 19. Social sustainability report

When the focal company and all of its suppliers have completed their environmental and social assessments, the company creates orders. To create an order, the focal company first must create a digital record of the product. In the scenario, the focal company registers the product and product's production processes to the system. The product organic cotton t-shirt and the production steps of harvest, harvest transport, yarn manufacturing, yarn transport, fabric formation, dyeing, fabric transport, cut and sew, cut and sew transport, and storage are added to the system (Figure 20 and 21).

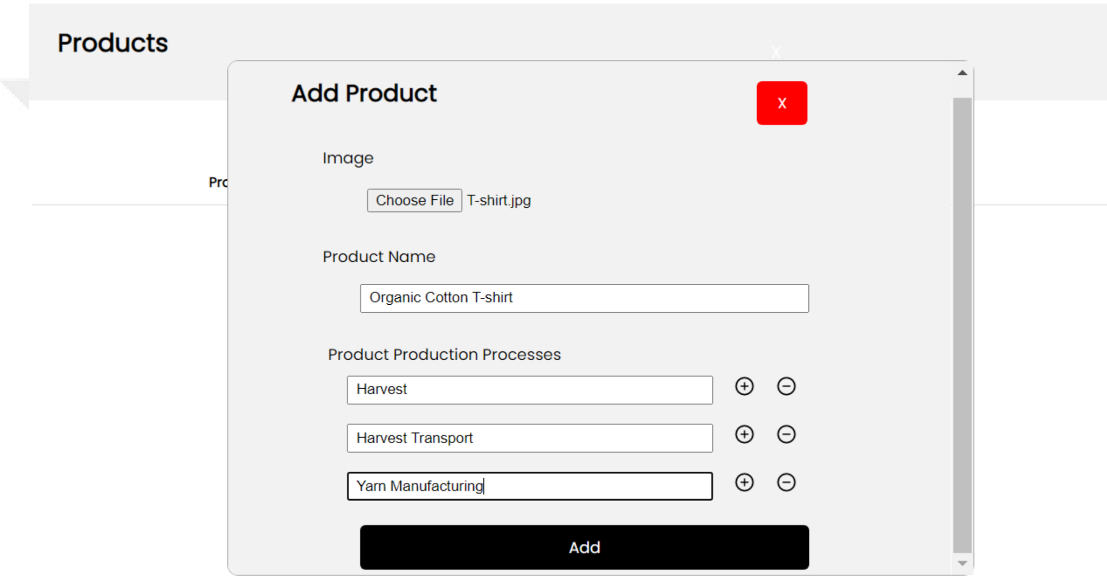


Figure 20. The focal company adds product

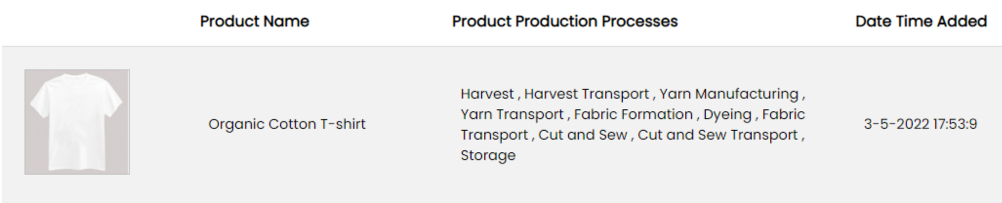


Figure 21. The product is added to the system

From the dashboard page, order and shipment details are displayed (Figure 22). The focal company can create orders and suppliers can sent or receive order shipments.

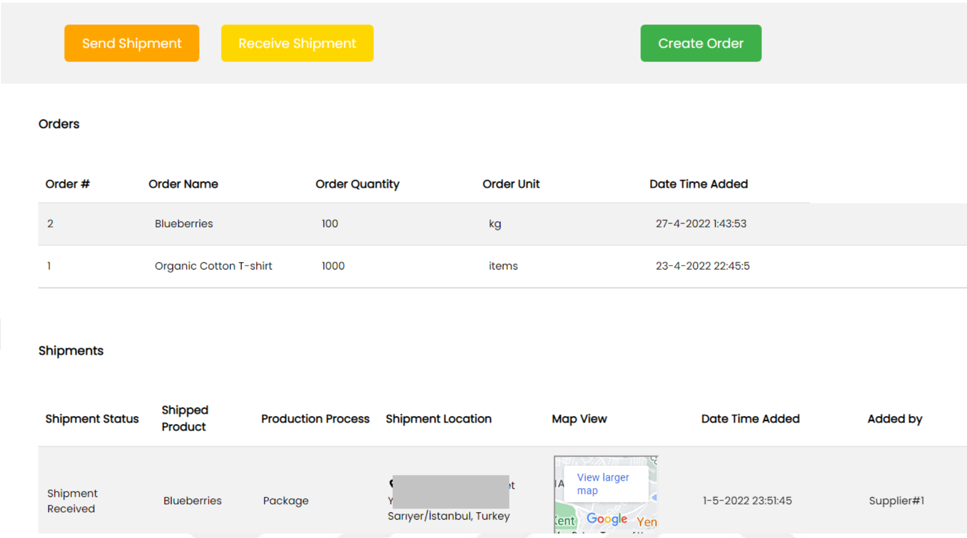


Figure 22. Dashboard page

After registering the product, the focal company creates an order. In this scenario, production of 1000 t-shirts are ordered (Figure 23 and 24). The permission to add products and orders is only given to the focal company.

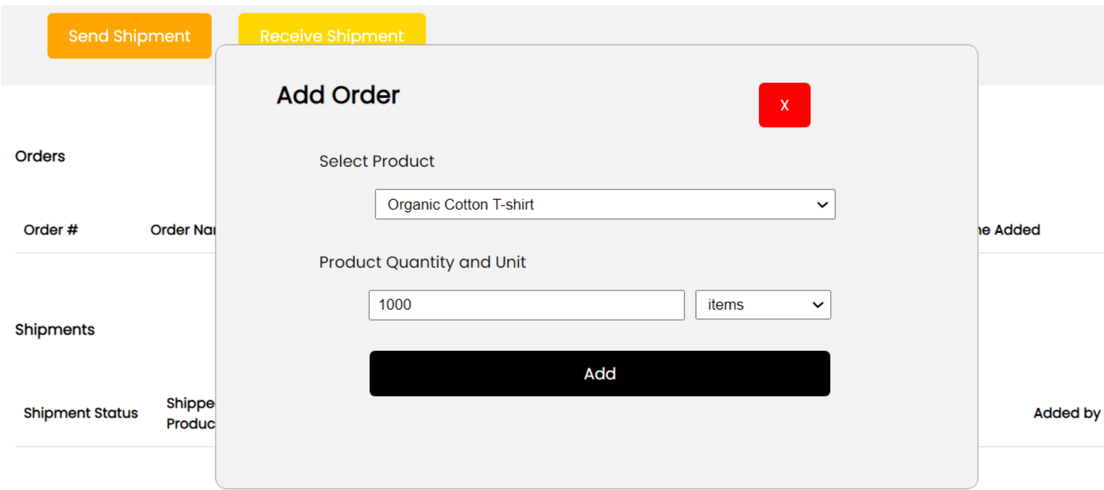


Figure 23. The focal company adds order

Order #	Order Name	Order Quantity	Order Unit	Date Time Added
1	Organic Cotton T-shirt	1000	items	3-5-2022 17:56:42

Figure 24. The order is added to the system

Later, the suppliers' send or receive the shipments of the order. When sending or receiving the shipments, each supplier selects the order and their production stage (Figure 25 and 26). As shipment is sent or received the real-time location (latitude and longitude), descriptive name of the location and the time information is obtained.

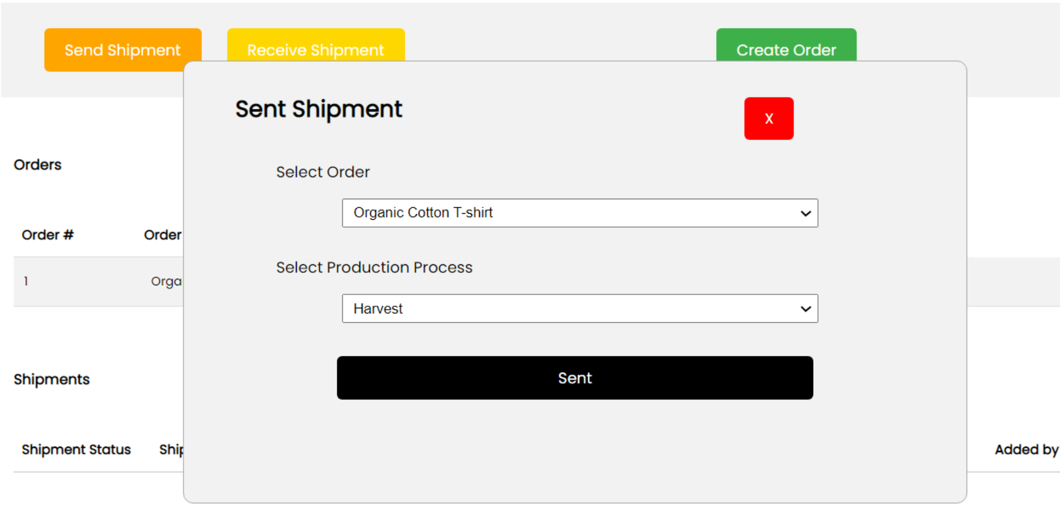


Figure 25. The supplier sent the shipment of the order

Shipments

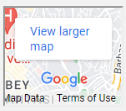
Shipment Status	Shipped Order	Production Process	Shipment Location	Map View	Date Time Added	Added by
Shipment Sent	Organic Cotton T-shirt	Harvest	Dikilitaş, Hakkı Yeten Cd. No:14, 34349 Beşiktaş/İstanbul, Turkey		3-5-2022 18:25:9	Supplier#1

Figure 26. The shipment is added to the system

The life cycle inventory for each production process can be done after relevant production stages are completed. The company or the suppliers enter information to LCI form of the material flow for their production stage (Figure 27). After submitting the form, the system automatically calculates LCI indicators (Figure 28). The information collected for the life cycle inventory analysis can be found in the Appendix C under the title input description. The LCI analysis can later be used to conduct life cycle assessment of the product.

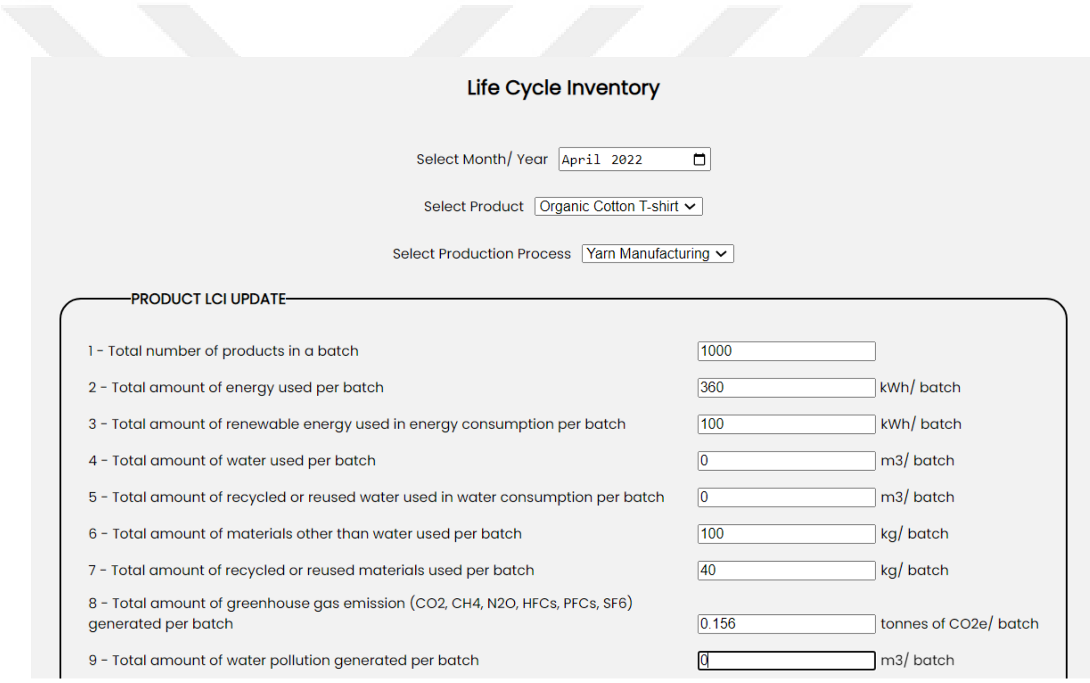


Figure 27. The supplier enters information into the LCI form

Life Cycle Inventory of Yarn Manufacturing of a Organic Cotton T-shirt

For the period Apr 2022 by Supplier#1

Categories	Indicators	Measurements	Values	Units
Natural Resources	Energy Consumption	Amount of energy used per unit of product	0.36	kWh/ unit of product
	Renewable Energy	Amount of renewable energy used in energy consumption per unit of product	0.10	kWh/ unit of product
		Percentage of renewable energy used per unit of product	27.78	%
	Water Consumption	Amount of water used per unit of product	0	m3/ unit of product
	Recycled Or Reused Water	Amount of recycled or reused water used in water consumption per unit of product	0	m3/ unit of product
		Percentage of recycled or reused water per unit of product	NaN	%
	Material Consumption	Amount of materials other than water used per unit of product	0.10	kg/ unit of product

Figure 28. Life cycle inventory analysis

From the reports page, stakeholders can view the LCI analysis chart (Figure 29). All the product production stages are displayed in the x axis of each chart. With these informations stakeholders can detect inefficacies in their production processes and they can find out about the environmental impact of each processes.

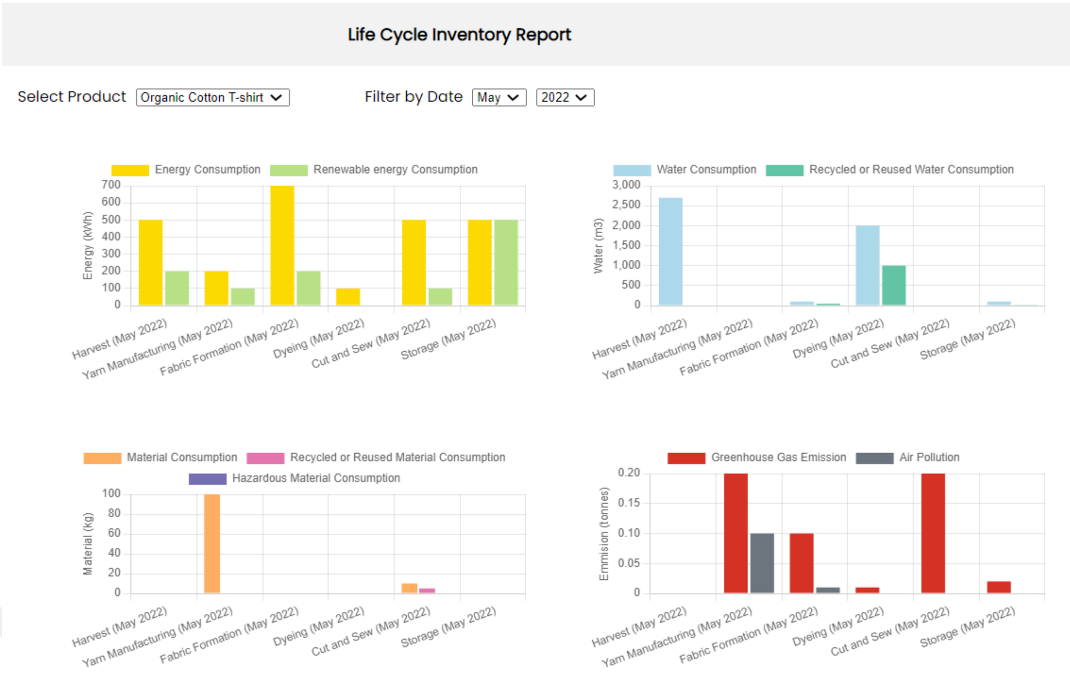


Figure 29. LCI report

Finally, when the order is completed, customers can see the entire product journey; the shipment locations and time, production stages and the suppliers (Figure 30). They can also display the environmental footprint of each production process and the environmental and social sustainability assessment of suppliers and the focal company.

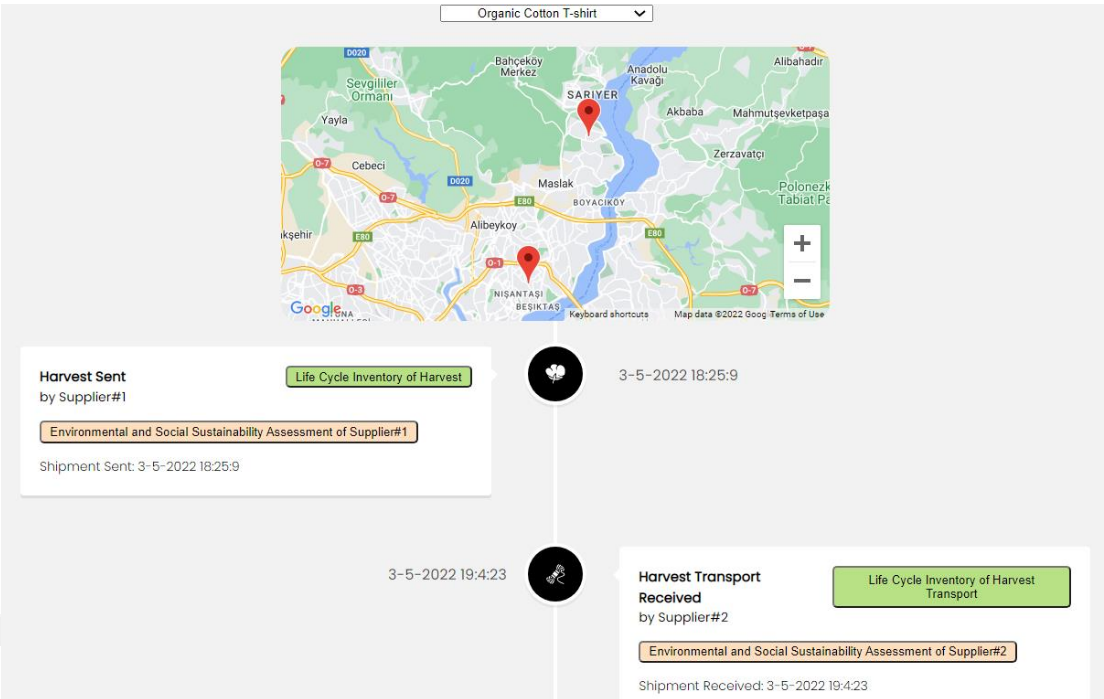


Figure 30. The product journey

CHAPTER 6

VALIDATION OF THE DESIGN

This thesis has presented the design and implementation of a blockchain-based DSS for measuring social and environmental sustainability. As a result of the system implementation, several goals have been accomplished. The achieved goals are tracking and tracing of product location and time, collecting various sustainability data from stakeholders and uploading them to blockchain, calculating key performance indicators and displaying them in tables and charts to share with stakeholders. The system can handle multiple product orders and shipments at the same time. The provided solution demonstrates the efficiency, effectiveness and flexibility of blockchain technology in addressing the challenges of supply chain sustainability assessments. Blockchain enables an agile trustworthy platform for collecting and sharing real-time sustainability information among value chain actors to guide them in decision making.

Due to the limited time, the delete and edit functions for orders, products, assessments, and shipments were excluded. Furthermore, the smart contract codes need to be optimized to lower Ethereum gas costs. An issue observed in the system implementation is the accuracy of the latitude and longitude data. The location information is obtained from HTML Geolocation. However, it is seen that at times the location accuracy was low. Thus, for more accurate location GPS or RFID tags can be used to track products. The user authentication of the system is done via Metamask and no database was used in the system development other than the local blockchain. However, for more comprehensive user authentication and data structures, an external database can be used. It is observed that the information collection part, where users enter relevant information about their sustainability measures, is a cumbersome task. Thus, the user interface of assessment forms can be altered for a more user-friendly experience. On the other hand, the relevant sustainability data can be collected from existing systems by system integrations rather than using forms.

6.1 Performance evaluation by a professional expert

The performance of the DSS is assessed by the sustainability manager of the textile company where the DSS is illustrated in Section 5.5.1. The DSS is demonstrated to the manager and she is asked to evaluate its performance with an interview (see Appendix F for the full version of the interview).

The results of the expert evaluation are very favorable. The blockchain-based DSS provides an effective, efficient, and flexible environment for measuring sustainability and tracing products in a supply chain. The expert agrees that the DSS is effective as it successfully fulfills its main functions. These functions are environmental and social sustainability measurement, tracking the time and location of the shipments, displaying the journey of the product, and preparing sustainability reports. The expert strongly agrees that The DSS is efficient as it decreases the total time spent on fulfilling the main functions and does not request any unnecessary information. However, she is neutral about the cost efficiency of the DSS. Furthermore, the system is flexible as it can adapt to a changing environment. It is strongly agreed that the parameters can be easily changed when necessary and can be easily adapted to changing market conditions such as new products, and customers, and it can also be adapted to changing supply chain structures, such as new suppliers, manufacturers, distributors, and retailers.

From the interview, it can be understood that there is a problem with tracing the origin of the products and there is a lack of available sustainability data of suppliers. She indicates that the DSS will be very useful for companies and these types of systems will start to be used very soon.

The manager gives some suggestions on the DSS. Firstly, she mentions that the system should include more production volume units such as liters. Secondly, the system should be adapted and made more user-friendly for users from all kinds of business segments such as textile, car manufacturers, and farmers so that they would use the system easily. She adds that the data requested should be clear, and the descriptions must be very specific, there should be explanatory boxes that include examples. Moreover, there should be a written summary and an interpretation of the assessment results in addition to graphical plots. As a result of the interview and questionnaire, with suggested improvements being completed, resistance to the adoption of DSS among users is not anticipated.

CHAPTER 7

CONCLUSION

Today, we consume millions of products all around the world without knowing much about where and how the products are made and their effects on the environment and society. Yet, as consumers, we are becoming more aware of climate crises and the significance of sustainability. This puts pressure on businesses to trace products back to their sources and measure sustainability performance beyond their first-tier suppliers.

Conventional supply chains have encountered several challenges, including a lack of advanced technologies, poor traceability, a lack of flexibility and distrust in the information flow. Despite business efforts, the progress of sustainable development has been slow. This is due to the failure of conventional methods and standards in measuring sustainability and in integrating sustainability into products, operations, and decisions. Organizations need to incorporate sustainability into their everyday business operations and measure and track performances. Hence, effective methods are required for assessing and quantifying sustainability impacts and establishing key performance metrics in the sustainable supply chain management.

In this thesis, a blockchain-based DSS is developed to measure the environmental and social performance of supply chains and to hold companies accountable for their sustainability impacts. Blockchain has promising features to support sustainability which are transparency, traceability, data security, integrity, and accountability. In the DSS, a quantitative assessment model was created to be used in the sustainability measurement of all supply chain actors. The blockchain-based system can be used to prove the origin of the products, track product journey throughout the supply chain, and measure supply chain sustainability. It is designed to collect the data from the supply chain actors, calculate their environmental and social performance assessments and prepare reports. The sustainability performance result and reports can be shared and viewed by stakeholders. These stakeholders can be companies, suppliers, customers, non-governmental organizations, and government agencies.

Companies can use this system to check if all suppliers have satisfactory environmental and social conditions. Moreover, they can compare environmental and social performance measurements to identify potential critical suppliers within their supply chains. The collected data on sustainability can be used to monitor, evaluate and certify if suppliers meet the ethical standards and requirements during the manufacturing process. This system also ensures that sustainability is measured regularly. It can also be used as a benchmarking tool in sustainable supply chain.

The DSS enables companies to monitor and trace real-time occurrences of shipments and the entire product lifecycle. This system can be utilized to collect data for better product design and manufacturing. Consequently, customers will be able to access information about production and transportation of goods and would be able to choose sustainable products. Moreover, government agencies can use this system to issue taxes or regulations on suppliers who do not comply with sustainability standards. Lastly, NGOs can ease and speed up their certification and audit processes with the information obtained from the blockchain-based DSS.

The proposed system aims to improve four SDGs of the UN. SDG 9 is achieved by promoting sustainable industrialization and fostering innovation. SDG 12 is attained by creating sustainable consumption and production patterns. SDG 13 is carried out by taking urgent action to tackle climate change, and SDG 17 is accomplished by strengthening the implementation and revitalizing of the global partnership for sustainable development.

There have been several challenges and limitations faced during the development of the system. In this study, a prototype for a blockchain based-DSS to assess the sustainability performances of supply chains is provided. The design of the DSS interface and database can be improved and smart contract codes can be optimized for real applications. For future work, the DSS can be applied to real world cases using RFID tags to track the product and it can be deployed on the real Ethereum network which is integrated to the ERP system. The DSS can be further developed for the measurement of LCA.

Organizational sustainability is associated with sustainable development. As it can be seen from SDGs and the Green Deal initiatives, the world is transitioning towards sustainability. The change will eventually come and innovations like blockchain will play a big role in this transition to a better world. Companies will need to measure and acknowledge their environmental and social performance to take action and integrate sustainable solutions. Thus, this system can be seen as a building block to help combat climate change and other humanitarian crises.

The 21st century is the century of awareness of our connections with the environment and society to repair human-induced damages and combat the threats the world faces. This is only a foundation for change. The real change will happen collectively where the companies and customers have the right information to choose their suppliers and what they purchase respectively.

APPENDIX A

ENVIRONMENTAL SUSTAINABILITY INDICATORS

Indicator Category	Indicators	KPI Measure	Measurement Unit	Input Description	Input Values	Output Values	Scale
Natural Resources	Energy consumption	Amount of energy used per month	kWh/ month	Total amount of energy used per month	100	100	non-negative value
	Energy efficiency	Amount of energy reduced per month	kWh/ month	Total amount of energy used in previous month - Total amount of energy used in current month	120 - 100	20	non-negative value
		Percentage of energy reduced per month	% of kWh/ month	(Total amount of energy used in previous month - Total amount of energy used in current month) x 100 Total amount of energy used previous month	(120 - 100) x 100 120	16,6	[0 - 100]
	Renewable energy	Amount of renewable energy used in energy consumption per month	kWh/ month	Total amount of renewable energy used in energy consumption per month	40	40	non-negative value
		Percentage of renewable energy used in energy consumption per month	% of kWh/ month	Total amount of renewable energy used in energy consumption per month x 100 Total amount of energy used per month	40 x 100 100	40	[0 - 100]
	Water consumption	Amount of water used per month	m3/ month	Total amount of water used per month	80	80	non-negative value
	Recycled or reused water	Amount of recycled or reused water used in water consumption per month	m3/ month	Total amount of recycled or reused water used in water consumption per month	20	20	non-negative value
		Percentage of recycled or reused water used in water consumption per month	% of m3/ month	Total amount of recycled or reused water used in water consumption per month x 100 Total amount of water used per month	20 x 100 80	25	[0 - 100]
	Material consumption	Amount of materials other than water used per month	kg/ month	Total amount of materials other than water used per month	100	100	non-negative value
	Material efficiency	Amount of materials reduced per month	kg/ month	Total amount of materials used in previous month - Total amount of materials used in current month	110 - 100	10	non-negative value
		Percentage of materials reduced per month	% of kg/ month	(Total amount of materials used in previous month - Total amount of materials used in current month) x 100 Total amount of materials used in previous month	(110 - 100) x 100 100	10	[0 - 100]
	Recycled or reused materials	Amount of recycled or reused materials used in material consumption per month	kg/ month	Total amount of recycled or reused materials used in material consumption per month	40	40	non-negative value
		Percentage of recycled or reused materials used in material consumption per month	% of kg/ month	Total amount of recycled or reused materials used in material consumption per month x 100 Total amount of materials used per month	40 x 100 100	40	[0 - 100]
	Land use	Amount of land owned, leased, or managed for production activities or extractive use	m2	Total amount of land owned, leased, or managed for production activities or extractive use	1000	1000	non-negative value
	Biodiversity	Existence of biodiversity policy	biodiversity policy	Is there a biodiversity policy?	Yes	Yes	Yes/ No
		Existence of activities and operations on protected and sensitive areas	activities and operations	Are there activities and operations on protected and sensitive areas? (e.g., IUCN protected area categories 1–4, world heritage sites, and biosphere reserves)	No	No	Yes/ No

Indicator Category	Indicators	KPI Measure	Measurement Unit	Input Description	Input Values	Output Values	Scale
Pollution and Waste Management	Greenhouse gas emission	Amount of greenhouse gas emission (CO2, CH4, N2O, HFCs, PFCs, SF6) generated per month	tonnes of CO2e/ month	Total amount of greenhouse gas emission (CO2, CH4, N2O, HFCs, PFCs, SF6) generated per month	0.04	0.04	non-negative value
	Water pollution	Amount of water pollution per month	m3/ month	Total amount of water pollution generated per month	0	0	non-negative value
		Type of water pollution	water pollution type	Choose the type(s) of water pollution	None	None	Oil, fuel, wastes, chemicals, none
	Land pollution	Amount of land pollution per month	m2/ month	Total amount of land pollution generated per month	0	0	non-negative value
		Type of land pollution	land pollution type	Choose the type(s) of land pollution	None	None	Oil, fuel, wastes, chemicals, none
	Air pollution	Amount of air emission (NOx, SOx) generated per month	tonnes/ month	Total amount of air emmision (NOx, SOx) generated per month	0,016	0,016	non-negative value
	Use of hazardous materials	Amount of hazardous materials used per month	kg/ month	Total amount of hazardous materials used per month	0	0	non-negative value
	Solid waste	Amount of solid waste generated per month	kg/ month	Total amount of solid waste generated per month	20	20	non-negative value
		Amount of solid waste recycled or reused per month	kg/ month	Total amount of solid waste recycled or reused per month	10	10	non-negative value
		Percentage of solid waste recycled or reused per month	% of kg/ month	Total amount of solid waste recycled or reused per month x 100 / Total amount of solid waste generated per month	10 x 100 / 20	50	[0 - 100]
		Type of solid waste destination	waste destination type	Choose the type(s) of solid waste destination	Recycling	Recycling	Composting, reuse, recycling, recovery, incineration, landfilling, none
	Wastewater	Amount of waste water generated per month	m3/ month	Total amount of waste water generated per month	80	80	non-negative value
		Amount of waste water recycled or reused per month	m3/ month	Total amount of waste water recycled or reused per month	40	40	non-negative value
		Percentage of waste water recycled or reused per month	% of m3/ month	Total amount of waste water recycled or reused per month x 100 / Total amount of waste water generated per month	40 x 100 / 80	50	[0 - 100]
		Type of waste water destination	waste destination type	Choose the type(s) of waste water destination	Reuse	Reuse	Composting, reuse, recycling, recovery, incineration, landfilling, none

Indicator Category	Indicators	KPI Measure	Measurement Unit	Input Description	Input Values	Output Values	Scale
Pollution and Waste Management	Hazardous waste	Amount of hazardous waste generated per month	kg/ month	Total amount of hazardous waste generated per month	0	0	non-negative value
	Product recyclability	Percentage of products produced that are recyclable or reusable per month	% products/ month	Total number of products produced that are recyclable or reusable per month x 100	250 x 100	50	[0 - 100]
				Total number of products produced per month	500		
	Green packaging and labeling	Percentage of products produced with eco-friendly packaging and labeling per month	% products/ month	Total number of products produced with eco-friendly packaging and labeling per month x 100	500 x 100	100	[0 - 100]
				Total number of products produced per month	500		
Operations Management and Performance Measurement	Environmental management system	Existence of external certifications regarding environmental standards	environmental standards	Choose the external certification(s) regarding environmental standards	ISO 14001	ISO 14001	ISO 14001, None
	Cleaner technology	Type of clean technology used	clean technology type	Choose the type(s) of clean technology used	Recycling, renewable energy	Recycling, renewable energy	Recycling, renewable energy, green transportation, electric motors, green chemistry, lighting,
	Supplier sustainability assessment	Percentage of suppliers monitored on environmental sustainability per year	% of suppliers/ year	Total number of suppliers monitored on environmental sustainability per year	3 x 100	60	[0 - 100]
				Total number of suppliers per year	5		

APPENDIX B

SOCIAL SUSTAINABILITY INDICATORS

Indicator Category	Indicators	KPI Measurement	Measurement Unit	Input Description	Input Values	Output Values	Scale
Labor Practices	Employee training and development	Average training hours per employee per year	hours/ year	Total number of training hours provided to employees per year	1200	40	non-negative value
				Total number of trained employees per year	30		
		Percentage of employees trained per year	% of employees	Total number of trained employees per year x 100	30 x 100	75	[0 - 100]
				Total number of employees	40		
	Employee turnover	Employee turnover per year	employee turnover/ year	Total number of employees who resigned or have been made redundant per year	2	0.2	non-negative value
				Total number of hired employees per year	10		
	Full and part-time employees	Percentage of full-time employees	% of employees	Total number of full-time employees x 100	30 x 100	75	[0 - 100]
				Total number of employees	40		
		Percentage part-time employees	% of employees	100 - Percentage of full-time employees	100 - 75	15	[0 - 100]
	Hours of work	Average contractual weekly working hours per employee to working hours regulated by the public law	hours/ month	Average contractual weekly working hours per full-time employee per month	45	1	non-negative value
				Working hours regulated by the public law per month	45		
		Average weekly overtime hours per employee per month	hours/ month	Average weekly overtime hours per employee per month	0	0	non-negative value
	Fair wage	Percentage of employee wage to the minimum wage	% of employee wage	Average employee wage x 100	6000 x 100	141	[0 - 100]
				National minimum wage	4250		
		Percentage of full-time employees earning below minimum wage	% of employees earning below minimum wage	Total number of full-time employees earning below minimum wage x 100	0 x 100	0	[0 - 100]
				Total number of employees	40		
	Social benefits and security	Percentage of employees entitled to social benefits	% of employees	Total number of employees entitled to health insurance, parental leave, unemployment, disability and invalidity coverage, retirement provision	30 x 100	75	[0 - 100]
				Total number of employees	40		
	Gender diversity	Wage diversity of genders	female wage/ male wage	Average female employee wage	6000	1	non-negative value
				Average male employee wage	6000		
		Employee gender diversity	female employees/ male employees	Total number of female employees	22	1,2	non-negative value
				Total number of male employees	18		
		Percentage of female employees in board of directors and management positions per year	% of employees/ year	Total number of female employees in board of director and management positions per year x 100	3 x 100	60	[0 - 100]
				Total number of employees in board of director and management positions per year	5		
	Diversity among the workforce	Percentage of disabled employees	% of employees	Total number of disabled employees x 100	0 x 100	0	[0 - 100]
				Total number of employees	40		
		Percentage of minority employees	% of employees	Total number of minority employees x 100	4 x 100	10	[0 - 100]
				Total number of employees	40		
		Percentage of employees with age over 65	% of employees	Total number of older employees x 100	0 x 100	0	[0 - 100]
				Total number of employees	40		
	Social standards (SA8000, ISO26000)	Existence of external certifications regarding social standards	social standards	Choose the external certification(s) regarding social standards and supplier's code of conduct	None	None	SA8000, ISO26000, None

Indicator Category	Indicators	KPI Measurement	Measurement Unit	Input Description	Input Values	Output Values	Scale
Health and Safety	Occupational health and safety	Occupational health and safety compliance	health and safety compliance	Is there compliance with ILO Guidelines for Occupational Health Management Systems?	Yes	Yes	Yes/ No
		Existence of fire-fighting equipment and emergency exits	fire-fighting equipment and emergency exits	Is there fire-fighting equipment and emergency exits?	Yes	Yes	Yes/ No
		Provision of medical assistance and first aid	medical assistance and first aid	Is there provision of medical assistance and first aid?	Yes	Yes	Yes/ No
		Access to drinking water and sanitation	drinking water and sanitation	Is there access to water and sanitation?	Yes	Yes	Yes/ No
		Provision of protective gear	protective gear	Is there provision of protective gear?	Yes	Yes	Yes/ No
	Accidents	Work accidents per year	accidents/ year	Total number of work accidents per year	0	0	non-negative value
Human Rights	Freedom of association	Presence of unions within the organization	presence of unions	Are there union(s) within the organization?	Yes	Yes	Yes/ No
		Percentage of employees joined to labor unions	% of employees	Total number of employees joined to labor unions x 100 / Total number of employees	25 x 100 / 40	62,5	[0 - 100]
	Collective bargaining agreements	Percentage of employees covered by collective bargaining agreements	% of employees	Total number of employees covered by collective bargaining agreements x 100 / Total number of employees	40 x 100 / 40	1	[0 - 100]
	Discrimination	Discrimination incidents per year	incidents/ year	Total number of discrimination incidents in terms of race, gender, sexual orientation, religion, disability, and age per year	0	0	non-negative value
	Child and forced labor	Child labor	employees	Total number of child labor	0	0	non-negative value
		Forced labor	employees	Total number of forced labor	0	0	non-negative value
	Rights of indigenous people	Violation of the rights of indigenous people per year	incidents/ year	Total number of incidents of violating the rights of indigenous people per year	0	0	non-negative value
Society	Job localization	Percentage of local employees	% of employees	Total number of local employees x 100 / Total number of employees	36 x 100 / 40	90	[0 - 100]
	Source localization	Percentage of local suppliers	% of employees	Total number of local suppliers x 100 / Total number of suppliers	5 x 100 / 5	100	[0 - 100]
	Community development	Percentage of charity donations to earnings per year	% of donations/ year	Total amount of donations made x 100 / Total amount of pre-tax earnings	2,000,000 x 100 / 8,000,000	25	[0 - 100]
	Corruption	Corruption incidents per year	incidents/ year	Total number of incidents of corruption per year	0	0	non-negative value
	Anti-competitive behavior	Legal actions regarding anti-competitive behavior per year	legal actions/ year	Total number of legal actions pending or completed regarding anti-competitive behavior per year	0	0	non-negative value
	Supplier sustainability assessment	Percentage of suppliers monitored on social sustainability per year	% of suppliers/ year	Total number of suppliers monitored on social sustainability per year x 100 / Total number of suppliers per year	4 x 100 / 5	80	[0 - 100]
Product Responsibility	Customer health and safety	Percentage of products and services for which health and safety impacts are assessed	% of products and services	Total number of products and services for which health and safety impacts are assessed x 100 / Total number of products and services	10 x 100 / 10	100	[0 - 100]
		Health and safety incidents concerning products and services per year	incidents/ year	Total number of health and safety incidents concerning products and services per year	0	0	non-negative value
	Respect for privacy	Customer privacy complaints per year	complaints/ year	Total number of customer privacy complaints per year	0	0	non-negative value
		Leaks, thefts, or losses of customer data per year	leaks, thefts, or losses/ year	Total number of leaks, thefts, or losses of customer data per year	0	0	non-negative value
	Customer satisfaction	Customer complaints per month	complaints/ month	Total number of customer complaints per month	5	5	non-negative value

APPENDIX C

LIFE CYCLE INVENTORY INDICATORS

Indicator Category	Indicators	KPI Measure	Measurement Unit	Input Description	Input Values	Output Values	Scale
Natural Resources	Energy consumption	Amount of energy used per unit of product	kWh/ unit of product	Total energy used to produce a batch of products	20	0.2	non-negative value
				Batch size	100		
	Renewable energy	Amount of renewable energy used in energy consumption per unit of product	kWh/ unit of product	Total amount of renewable energy used in energy consumption to produce a batch of products	10	0.1	non-negative value
				Batch size	100		
		Percentage of renewable energy used per unit of product	% of kWh/ unit of product	Total amount of renewable energy used in energy consumption to produce a batch of products x 100	10 x 100	50	[0 - 100]
				Total amount of energy used to produce a batch of products	20		
	Water consumption	Amount of water used per unit of product	m3/ unit of product	Total amount of water used to produce a batch of products	10	0.1	non-negative value
				Batch size	100		
	Recycled or reused water	Amount of recycled or reused water used in water consumption per unit of product	m3/ unit of product	Total amount of recycled or reused water used in water consumption to produce a batch of products	5	0.05	non-negative value
				Batch size	100		
		Percentage of recycled or reused water per unit of product	% of m3/ unit of product	Total amount of recycled or reused water used in water consumption to produce a batch of products x 100	5 x 100	50	[0 - 100]
				Total amount of water used to produce a batch of products	10		
	Material consumption	Amount of materials other than water used per unit of product	kg/ unit of product	Total amount of materials other than water used to produce a batch of products	20	0.2	non-negative value
				Batch size	100		
	Recycled or reused materials	Amount of recycled or reused materials used in material consumption per unit of product	kg/ unit of product	Total amount of recycled or reused materials used in material consumption to produce a batch of products	10	0.1	non-negative value
				Batch size	100		
		Percentage of recycled or reused materials used in material consumption per unit of product	% of kg/ unit of product	Total amount of recycled or reused materials used in material consumption to produce a batch of products x 100	10 x 100	50	[0 - 100]
				Total amount of materials used to produce a batch of products	20		
Pollution and Waste Management	Greenhouse gas emission	Amount of greenhouse gas emission (CO2, CH4, N2O, HFCs, PFCs, SF6) generated per unit of product	tonnes of CO2e/ unit of product	Total amount of greenhouse gas emission generated to produce a batch of products	0.01	0.0001	non-negative value
				Batch size	100		
	Air pollution	Amount of air emission (NOx, SOx) generated per unit of product	tonnes/ unit of product	Total amount of air emission generated to produce a batch of products	0	0	non-negative value
				Batch size	100		
	Water pollution	Amount of water pollution generated per unit of product	m3/ unit of product	Total amount of water pollution generated to produce a batch of products	0	0	non-negative value
				Batch size	100		
		Type of water pollution	water pollution type	Choose the type(s) of water pollution	None	None	Oil, fuel, wastes, chemicals, none
	Land pollution	Amount of land pollution generated per unit of product	kg/ unit of product	Total amount of land pollution amount generated to produce a batch of products	0	0	non-negative value
				Batch size	100		
		Type of land pollution	land pollution type	Choose the type(s) of land pollution	None	None	Oil, fuel, wastes, chemicals, none
	Use of hazardous materials	Amount of hazardous materials used per unit of product	kg/ unit of product	Total amount of hazardous materials used to produce a batch of products	0	0	non-negative value
				Batch size	100		

Indicator Category	Indicators	KPI Measure	Measurement Unit	Input Description	Input Values	Output Values	Scale
Pollution and Waste Management	Solid waste	Amount of solid waste generated per unit of product	kg/ unit of product	Total amount of solid waste generated to produce a batch of products	5	0.05	non-negative value
				Batch size	100		
		Amount of solid waste recycled or reused per unit of product	kg/ unit of product	Total amount of solid waste recycled or reused to produce a batch of products	2	0.02	non-negative value
				Batch size	100		
		Percentage of solid waste recycled or reused per unit of product	% of kg/ unit of product	Total amount of solid waste recycled or reused to produce a batch of products x 100	2 x 100	40	[0 - 100]
				Total amount of solid waste generated to produce a batch of products	5		
		Type of solid waste destination	waste destination type	Choose the type(s) of solid waste destination	Recycling	Recycling	Composting, reuse, recycling, recovery, incineration, landfilling, none
	Wastewater	Amount of wastewater generated per unit of product	kg/ unit of product	Total amount of wastewater generated to produce a batch of products	10	0.1	non-negative value
				Batch size	100		
		Amount of wastewater recycled or reused per unit of product	m3/ unit of product	Total amount of wastewater recycled or reused to produce a batch of products	5	0.05	non-negative value
				Batch size	100		
		Percentage of wastewater recycled or reused per unit of product	% of m3/ unit of product	Total amount of wastewater recycled or reused to produce a batch of products x 100	5 x 100	50	[0 - 100]
				Total amount of wastewater generated to produce a batch of products	10		
		Type of wastewater destination	waste destination type	Choose the type(s) of wastewater destination	Reuse	Reuse	Composting, reuse, recycling, recovery, incineration, landfilling, none
	Hazardous waste	Amount of hazardous waste generated per unit of product	kg/ unit of product	Total amount of hazardous waste generated to produce a batch of products	0	0	non-negative value
				Batch size	100		
	Product recyclability	Whether the product produced is recyclable or reusable	product recyclability or reusability	Is the product produced recyclable or reusable?	Yes	Yes	Yes/ No
	Green packaging and labeling	Whether the product has eco-friendly packaging and labeling	eco-friendly packaging and labeling	Does the product has eco-friendly package and label?	No	No	Yes/ No

APPENDIX D

ORIGIN SMART CONTRACT CODE

```
pragma solidity >=0.4.22 <0.9.0;

contract Origin {

    uint public productCount = 0;
    uint public orderCount = 0;
    uint public shipmentCount = 0;
    address owner = 0x3421668462324bFB48EA07D0B12243091CD09759;

    mapping (uint => Product) public products;
    mapping (uint => Order) public orders;
    mapping (uint => Shipment) public shipments;

    constructor() public {
    }

    modifier onlyOwner() {
      require(msg.sender == owner);
      _;
    }

    struct Product {
        uint id;
        string name;
        string image;
        string process;
        string date;
        address account;
    }

    event ProductAdded(
        uint id,
        string name,
        string image,
        string process,
        string date,
        address account
    );

    function addProduct(string memory _name, string memory _image,
string memory _process, string memory _date) public onlyOwner {
        require(bytes(_name).length != 0);
        require(bytes(_image).length != 0);
        require(bytes(_process).length != 0);
        require(bytes(_date).length != 0);
```

```
        productCount++;
        products[productCount] = Product(productCount, _name,_image,
_process, _date, msg.sender);
        emit ProductAdded(productCount, _name, _image, _process, _date,
msg.sender);
    }

    struct Order {
        uint id;
        string name;
        string quantity;
        string unit;
        string date;
        address account;
    }

    event OrderAdded(
        uint id,
        string name,
        string quantity,
        string unit,
        string date,
        address account
    );

    function addOrder(string memory _name, string memory _quantity,
string memory _unit, string memory _date) public onlyOwner {
        require(bytes(_name).length != 0);
        require(bytes(_quantity).length != 0);
        require(bytes(_unit).length != 0);
        require(bytes(_date).length != 0);
        orderCount++;
        orders[orderCount] = Order(orderCount, _name, _quantity, _unit,
_date, msg.sender);
        emit OrderAdded(orderCount, _name, _quantity, _unit, _date,
msg.sender);
    }

    struct Shipment {
        uint id;
        string shipType;
        string place;
        string latlong;
        string date;
        address account;
        string product;
        string process;
    }
```

```
    event ShipmentAdded(
        uint id,
        string shipType,
        string place,
        string latlong,
        string date,
        address account,
        string product,
        string process
    );

    function addShipment(string memory _shipType, string memory
_place,  string memory _latlong,
    string memory _date, string memory _product, string memory
_process) public {
        require(bytes(_shipType).length != 0);
        require(bytes(_latlong).length != 0);
        require(bytes(_date).length != 0);
        require(bytes(_product).length != 0);
        require(bytes(_process).length != 0);
        shipmentCount++;
        shipments[shipmentCount] = Shipment(shipmentCount, _shipType,
_place, _latlong, _date, msg.sender, _product, _process);
        emit ShipmentAdded(shipmentCount, _shipType, _place, _latlong,
_date, msg.sender, _product, _process);
    }

}
```

APPENDIX E

ASSESSMENTS SMART CONTRACT CODE

```
pragma solidity >=0.4.22 <0.9.0;

contract Assessments {

    uint public LCICount = 0;
    uint public enviroCount = 0;
    uint public socialCount = 0;
    uint public assessmentCount = 0;

    mapping (uint => LCI) public LCIs;
    mapping (uint => Enviro) public enviros;
    mapping (uint => Social) public socials;

    struct LCI {
        uint id;
        string assessType;
        string date;
        address account;
        string document;
        string month;
        string year;
        string process;
    }

    event LCIAdded(
        uint id,
        string assessType,
        string date,
        address account,
        string document,
        string month,
        string year,
        string process
    );

    struct Enviro {
        uint id;
        string assessType;
        string date;
        address account;
        string document;
        string month;
        string year;
    }
```

```
    event EnviroAdded(
        uint id,
        string assessType,
        string date,
        address account,
        string document,
        string month,
        string year
    );

    struct Social {
        uint id;
        string assessType;
        string date;
        address account;
        string document;
        string month;
        string year;
    }

    event SocialAdded(
        uint id,
        string assessType,
        string date,
        address account,
        string document,
        string month,
        string year
    );

    function addLCI(
        string memory _date,
        string memory _document,
        string memory _month,
        string memory _year,
        string memory _process
    ) public {
        require(bytes(_date).length != 0);
        require(bytes(_document).length != 0);
        require(bytes(_process).length != 0);
        LCICount++;
        assessmentCount++;
        LCIs[LCICount] = LCI(LCICount, "Life Cycle Inventory", _date,
msg.sender, _document, _month, _year, _process);
        emit LCIAdded(LCICount, "Life Cycle Inventory", _date,
msg.sender, _document, _month, _year, _process);
    }
    function addEnviro(
        string memory _date,
```

```
        string memory _document,
        string memory _month,
        string memory _year
    ) public {
        require(bytes(_date).length != 0);
        require(bytes(_document).length != 0);
        require(bytes(_month).length != 0);
        require(bytes(_year).length != 0);
        enviroCount++;
        assessmentCount++;
        enviros[enviroCount] = Enviro(enviroCount, "Environmental
Assessment", _date, msg.sender, _document, _month, _year);
        emit EnviroAdded(enviroCount, "Environmental Assessment",
_date, msg.sender, _document, _month, _year);
    }
    function addSocial(
        string memory _date,
        string memory _document,
        string memory _month,
        string memory _year
    ) public {
        require(bytes(_date).length != 0);
        require(bytes(_document).length != 0);
        require(bytes(_month).length != 0);
        require(bytes(_year).length != 0);
        socialCount++;
        assessmentCount++;
        socials[socialCount] = Social(socialCount, "Social Assessment",
_date, msg.sender, _document, _month, _year);
        emit SocialAdded(socialCount, "Social Assessment", _date,
msg.sender, _document, _month, _year);
    }
}
```

APPENDIX F

INTERVIEW WITH THE PROFESSIONAL EXPERT

Interview with the Sustainability Lead & Creative Team Manager

Nilüfer Okay (NO): How long have you been in this position?

Sustainability Manager (SM): About 2 years 6 months

NO: How do you measure environmental and social sustainability in the supply chain?

SM: The company we work with measures our carbon footprint and water footprint, including packaging and labels. B Corp measures the social impact at the end of the year, so we don't need to measure it as a company. Of course, non-B Corp suppliers need social performance measurement.

NO: Do you conduct life cycle assessment of the produced products?

SM: We do not work in the LCA field because we have too many product branches and we cannot get information from the manufacturers on the source of the cotton or yarn. Therefore, it is not known which manufacturer(s) produces the yarn. However, with a manufacturer we work with, we can get data on the source, and the company can calculate the water and electricity it uses while producing the product. We can calculate what we have data for, but otherwise, it becomes costly for us because at some point we get stuck tracing the origin of the product.

NO: Do you have any suggestions on how to improve this system?

SM: First of all, the products that everyone produces and the unit they use are different, some are measured by liters and some by volume. More detailed units are needed.

Secondly, you need to make it user-friendly according to how people from all kinds of business segments such as textile, car manufacturers, and farmers can use it. The system needs to be simplified and the requested data must be clear. For example, “the amount of material used” is a very open question, or “the amount of recycled or reused materials” what kind of materials are recycled or reused?. The description must be very specific and there should be a question mark icon and explanatory boxes that includes examples.

Another suggestion is, that in the report section, besides making graphics, there should be a written summary interpretation. You should give a written brief about the assessment results. After all, I may not be able to interpret every data I see. At the end of the day, when I receive a written document, there is at least a written output while writing my end-of-year impact report. It's not just about numbers and indicators. Having a written report makes me say that the money I paid for the system is worth it.

NO: Do you think companies will use this system?

SM: This is a system that companies will start using a lot. We closed the deal with a company for environmental impact assessment about 3 months ago. Since then, their customers have increased. There are different companies, from various industrial sectors, from producers to companies like us, that started to conduct environmental assessments.

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