Blockchain-Based Carbon Emissions Tracking in Supply Chains: A Smart Contract Solution for Scope 3 Reporting

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Abstract: The forthcoming European regulatory mandates, which require companies—including non-European entities with operations in Europe—to report indirect emissions within their value chains by 2025, present significant challenges. These include the difficulty of tracking emissions from activities outside the company's direct control, such as transport-related emissions from vehicles not owned by the entity. Our project proposes a solution through the development of a smart contract based on Ethereum blockchain technology, aimed at enhancing sustainable supply chain management. This smart contract facilitates the transparent and accurate reporting of Scope 3 greenhouse gas emissions, thereby addressing issues of under-reporting and opacity. The methodology employs a distance-based calculation for emissions, chosen for its relevance to standard business operations and its capacity to streamline the estimation process. A case study on the global shipment journey of an electronic control unit lot illustrates the application's functionality, demonstrating the system's ability to provide detailed emissions insights across a complex, multimodal logistics pathway. The study is aligned with upcoming regulatory requirements, offering an immutable, transparent ledger for emissions data. Future improvements aim to enhance the system's accuracy and user engagement, expanding the scope to include a wider range of emissions categories and incorporating advanced technologies for data collection and analysis.

Keywords: Supply Chain Management; Sustainability; Environmental Footprint; Blockchain; Ethereum

1. Introduction

The European Union (EU) approved the Corporate Sustainability Reporting Directive (CSRD) in 2022. By 2025, European companies will be required to publish detailed information on their sustainability impacts (European Parliament & Council of the European Union 2022). Additionally, the accounting of Scope 3 emissions will become mandatory. Scope 3 emissions refer to Greenhouse Gas (GHG) emissions that occur in the undertaking's upstream and downstream value chain, beyond the undertaking's direct emissions (Scope 1) and indirect energy emissions (Scope 2). The only economic sectors where direct emissions are predominant are energy, raw material extraction, agriculture, and transportation. On the other hand, the supply chain frequently accounts for 70% or more of the carbon footprint of organisations (Schmidt, Nill & Scholz 2022) and of the overall product carbon footprint (e.g., 82% in the automotive industry) (Buettner 2022). Analysing the rapid growth of global indirect emissions between 1995 and 2015, Hertwich & Wood (2018) found an increasing importance of supply chain emissions in the global economy, with the industry sector accounting for 32 $PgCO_2$ over the global 45 $PgCO_2$, reasonably due to the long supply chain in industry. Notably, this awareness shifts the interest of multi-national corporations in scope 3 emissions tracking along their upstream and downstream value chains, a complex task requiring the engagement of multi-tier actors (Patchell 2018). On the other hand, collaboration with suppliers and customers can enhance the environmental performance of processes and products (Koomen, Bouchery & Tan 2023).

The European Commission aims to reduce transport GHG emissions by up to 60% by 2050. This target includes freight transport emissions, posing specific challenges due to the anticipated increase in goods transport linked to future economic growth. A limited number of companies account for the emissions from the transportation activities of both upstream and downstream processes, underscoring the need for new and validated models to support decision-making processes for the sustainable reduction of CO_2e emissions (Dehdari, Wlcek & Furmans 2023). Many companies have begun to account for the emissions from the movement of goods; however, the majority of environmental, social, and governance (ESG) disclosures do not include these emissions (Nowlan et al. 2021).

The traditional linear supply chain concept, where individual actors play in a fragmented manner, has been progressively replaced by a cooperative and synergistic approach. Collaboration among various stakeholders has become crucial to meeting changing customers' needs and the challenges of a competitive and globalised market. Integrated systems are nowadays paradigmatic for real-time information sharing across the value chain (Wu et al. 2016). Blockchain technology has established itself as a potent tool for the creation of distributed and immutable digital ledgers. These ledgers offer unprecedented opportunities for traceability, transparency, and the security of information throughout the entire supply chain (Rani, Sharma & Gupta 2024). Blockchain has a dominant role in accounting and auditing. The technology verifies transaction attributes and boosts a continuous information flow among participants, enhancing transparency and trust (Suta & Tóth 2023). The combination of blockchain and the Internet of Things (IoT) offers advantageous features. It provides a scalable solution to supply chain challenges through gateways that manage large volumes of data, thereby enhancing reliability and security. The significant investments required for sensors are mitigated by cloud services for storage. Blockchain is widely recognised as a powerful technology for sustainability accounting since it has potential for validating data, managing transactions, and measuring sustainability metrics like GHG emissions throughout industrial operations (Suta & Tóth 2023). Ethereum is a platform based on blockchain technology. One of the main native features, smart contracts, are self-executing contracts that are activated upon the fulfilment of agreed-upon conditions, enabling the development of customised applications known as Decentralised Apps (DApps). Smart contracts enhance transparency and accessibility, facilitating access to and sharing of information among all parties involved (Banerjee 2019).

The objective of this study is to propose a smart contract proof-of-concept for upstream transportation carbon accounting, developed in Solidity and Python, and tested through the Ganache Truffle suite. In Section 2, a literature review is provided to offer an overview of recent developments in carbon reporting and tracking and blockchain applications for carbon accounting. Section 3 describes the method and architecture in detail. Section 4 presents a case study, and Section 5 outlines the application's functionalities. Section 6 provides the conclusion of the paper.

2. Literature review

Measuring businesses' scope 3 emissions is similar to a value chain emissions audit, which requires quantifying emissions from upstream and downstream organisations. In turn, companies necessitate gathering information from other entities in the value chain beyond their own reporting control. In addition, while emissions generated upstream are far more consistent, undeniable, and standardised, downstream emissions are difficult to quantify since the share and the use phase of a product can be hardly determined (Schmidt et al. 2022).

The direct engagement of all suppliers at the multiple supply chains levels through surveys is highly complicated due to the complexity of the network and the need for willingness to share data (Patchell 2018). Schmidt et al. (2022) propose to use the suppliers' anonymous input data from their ERP systems combined with economic input-output analysis models. Another critical issue of scope 3 emissions accounting is related to the risk of double counting the emissions; in fact, the focal company's scope 3 emissions are other organisations' scope 1, 2, or 3 emissions (Ryan & Tiller 2022).

Large companies usually use generic data from commercially available databases for materials and processes outside the company associated with process analysis and input-output analysis. These methods lack defined methodology, calling into doubt the validity of the obtained data (Busch, Johnson & Pioch 2022). Moreover, sometimes organisations report scope 3 emissions inconsistently across different communication channels (Klaaßen & Stoll 2021).

Among the few studies analysing how to incorporate blockchain technologies into the GHG protocol, Diniz et al. (2021) evaluate the possibilities for implementing blockchain in scope 2 of the GHG Protocol involving a network of organisations in Brazil, showing how this technical solution can help businesses acquire critical competencies, overcome sharing obstacles, and promote indirect learning across the value chain. Chen et al. (2022) provide a framework for a blockchain-based application for the textile industry. The application helps to quantify carbon emissions from production, raw materials, and energy.

Rosado Da Cruz et al. (2020) propose an Ethereum smart contract-based platform to verify product origins and visualise the incremental carbon footprint at each production stage. Zhang et al. (2020) as well as Rolinck et al. (2021) attempt to integrate Life Cycle Assessment (LCA) methodology into the blockchain environment; however, they do not present a proof-of-concept.

Hao (2022) develops an Hyperledger Fabric blockchain platform to assess the carbon emissions of the chip multi-tier supply chain. Similarly, Alves, Cruz & Rosado Da Cruz (2022) build a platform to trace environmental and social indicators of the textile value chain. Here, a smart contract is deployed on the Hyperledger Fabric platform together with a full-stack Dapp architecture. Finally, Lee et al. (2023) propose a system to improve the visibility of environmental information in a multi-tier supply chain at the product level.

Our study aims at proposing a proof-of-concept for upstream transportation carbon accounting using smart contracts. This innovative approach applies the GHG Protocol quantification methodology through smart contracts, ensuring transparency and verifiability of data throughout the supply chain. This enhances the accuracy of carbon emissions accounting and provides a robust solution to overcome existing limitations, promoting broader adoption of blockchain for comprehensive and transparent carbon accounting.

3. Proposed system

3.1 Upstream carbon assessment

To calculate the Scope 3 emissions from upstream transportation and distribution (category 4), three methods are proposed: the fuel-based, the distance-based, and the spend-based method. Figure 1 summarises the decision-making process to calculate emissions from available data.

- The Fuel-based method involves applying appropriate emission factors to the fuel consumed.
- The Distance-based method involves accounting the amount of mass, distance, and shipment mode to apply a mass-distance emission factor.
- The Spend-based method calculates the amount of money spent for each mode and applies secondary emission factors.

Category 4 accounts for the reporting company’s Tier 1 or inbound/outbound logistics from vehicles and facilities not owned or controlled by the reporting company.

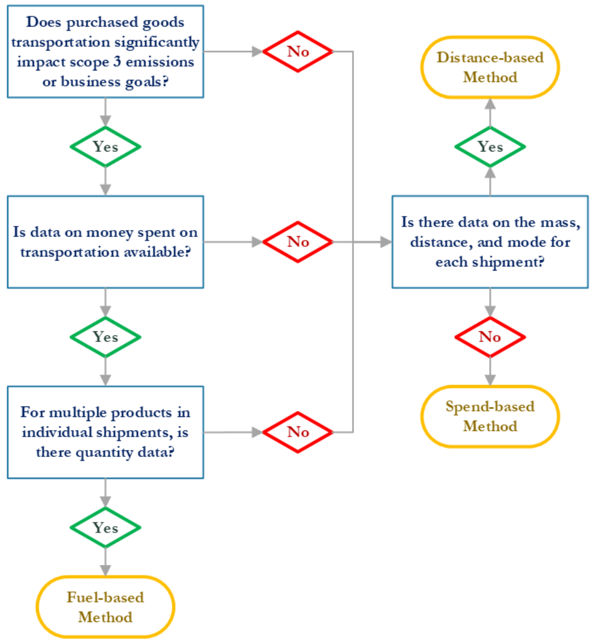


Figure 1 Calculation method decision tree

Fuel-based method. It should be used when companies can obtain data for fuel use from transport providers. Where fuel use data is unavailable, the company may deduce fuel use from the amount spent on fuel, the average price of fuel, the distance travelled, and efficiency (Eq. 1).

$$EI_{fuel-based} = \sum Q_f EF_f + \sum Q_e EF_e + \sum Q_r EF_r \tag{1}$$

Where $Q_r[litre]$ is the quantity of fuel consumed, $Q_e[kWh]$ the quantity of electricity consumed, and $Q_r[kg]$ the quantity of refrigerant leakage, followed by corresponding emission factor ($EF_f[kgCO_2e/litre]$, $EF_e[kgCO_2e/kWh]$, and $EF_r[kgCO_2e/kg]$).

Distance-based method. This method is particularly useful for organisations lacking access to specific fuel consumption or mileage data from their transport vehicles, especially when dealing with smaller shipments. Data needed for this calculation includes the mass or volume of products sold and the actual or shortest theoretical distance travelled, which can be sourced from transportation suppliers, online maps, or published distances (Eq. 2).

$$EI_{dist-based} = D \cdot M \cdot EF \tag{2}$$

The calculation involves multiplying the distance, $D[km]$, by either the mass $[kg \text{ or } t]$ or the volume of goods $[TEU]$, M, and by the specific emission factor, $EF[kgCO_2e/t \cdot km$ or $kgCO_2e/TEU \cdot km]$, for each mode of transport or vehicle type.

While actual distances are preferred, the distance-based method generally assumes average conditions, making it less accurate than the fuel-based method but still valuable when specific fuel data is unattainable.

Spend-based method. This approach is considered less accurate due to its higher levels of uncertainty compared to the fuel-based and distance-based methods, making it best suited for screening purposes.

$$EI_{spend-based} = C \cdot EF \tag{3}$$

It calculates emissions by multiplying the monetary amount spent C [$] on different types of transportation by relevant Environmentally Extended Input-Output (EEIO) emission factors, EF, which provide cradle-to-gate GHG emissions per unit of economic value $[kgCO_2e/\$]$ (Eq. 3).

To align with standard business practices, the smart contract is specifically designed to use a distance-based method for the tracking of emissions. It utilises average emission factors applicable to trucks, airplanes, and ships respectively, simplifying the estimation process and ensuring a straightforward approach to calculating the environmental impact of transport-related emissions within the supply chain.

3.2 System architecture

The proposed solution is focused on the interaction between a Tier-1 supplier and an OEM (Original Equipment Manufacturer). Tier 1 is responsible for tracking sold products, and the OEM wants to assess the related carbon footprint.

The primary function of this application is the formatting of data into useful, immutable, and easily readable structures, simplifying the retrospective reconstruction of the batch's journey from production to retail sale. Three Python applications manage interactions with the contract, enabling data updates and visualisation, as presented in Figure 2.

1. `contractDeployer.py`: A Python script that compiles the smart contract and uploads it to the blockchain network. It will be used by the supply chain manager to activate the CO_2 emissions tracking system.
2. `transferUpdater.py`: A Python script aimed at receiving batch data, processing it, and then sending it to the smart contract via a transaction that updates the blockchain state. It will be used by supply chain actors to actively track batch movements.

3. `pollutionViewer.py`: A Python script that connects to the smart contract, allowing the visualisation of data related to CO_2 emissions. It will be used by end stakeholders, equipped with the ID of the recently purchased product, to view the emissions attributable to their purchase.

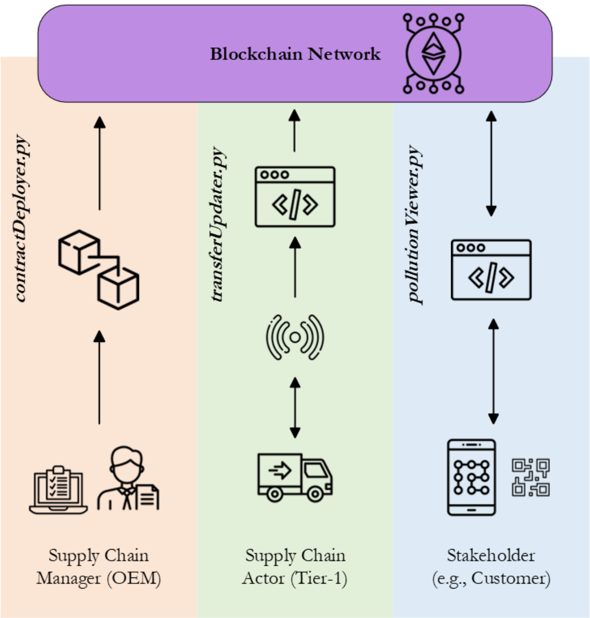


Figure 2 System architecture

The script `contractDeployer.py` compiles the contract through the *`compile_standard()`* method, provided by **`solcx`** package. An interface between Solidity and Python code is needed to let the two programming systems interact, called through the ABI (Application Binary Interface), an interface that defines which methods can be called and how they should be called. After the source code has been written, it is compiled into bytecode. This bytecode is what runs on the Ethereum Virtual Machine (EVM), allowing smart contracts to operate on the blockchain. Compilation is a crucial step in the development process with Solidity, as it ensures that the code is optimised and ready to be executed efficiently on the blockchain. Once these two parameters have been defined, it is possible to connect to the blockchain network using *`w3.eth.contract()`* method of **`web3`** library. The smart contract will automatically be assigned an address, through which its functions can be accessed, and it will be ready for use. An RFID sensor, or the scanning of a QR code, sends a signal to the transferUpdater.py application, containing the parameters listed on the tag placed on the lot. Calculations are delegated to an external Python file, `transferUpdater.py`, aiming at minimising operations charged to the contract. This script sends the data to the smart contract and executes the transaction. It is assumed that the data inputted by the sensor is correct; therefore, no checks on these values will be implemented, and furthermore, the ID assignment systems are different for every actor in the supply chain. Once the distance calculation is made, all the necessary values for the smart contract's operation are available. The Python programme `pollutionViewer.py` is designed to enable the visualisation of data processed by the smart contract.

3.3 Smart contract developing and testing

Source code `batchTracker.sol` is the developed smart contract, which can be deployed with Solidity versions equal to or subsequent to 0.8.0. It allows to track each delivery step during upstream distribution, saving data immutably on the blockchain. Solidity was chosen for developing the smart contract. Solidity is a programming language for developing smart contracts on several blockchain platforms, most notably Ethereum.

Within the smart contract, a struct named `Transfer` groups together variables of different types to collectively represent a shipped lot. This customisable data structure is crucial for representing complex concepts with multiple attributes neatly and simply. The struct is defined by parameters such as the new batch ID, previous batch ID, batch size, distance travelled, mode of transportation, and calculated CO_2e emissions.

Simultaneously, the `TransportMode` enum restricts the possible modes of transport to a limited set of values: truck, airplane, and ship. This ensures that the transportation mode variable within the transfer struct can only take on these predefined values, facilitating the management and interpretation of transport mode data. The contract sets constants to represent average CO_2e emission rates and transport capacities for trucks, airplanes, and ships. These values are used to calculate the CO_2e emissions for each transfer, based on the distance-based method.

The contract employs two primary mappings: `batchHistory` and `batchIdLinks`. The former maps each batch ID to an array of `Transfer` structures, enabling the tracking of every avocado batch's transport history. The latter mapping links each new batch ID to its preceding ID, facilitating the reconstruction of a batch's chain of transfers.

The contract implements three key functions: `calculateCO2Emissions`, `addTransfer`, and `getBatchHistory`. `calculateCO2Emissions` inputs the batch's weight, transportation mode, and travelled distance to calculate CO_2e emissions using the provided data and predefined constants. This internal function, though not altering the blockchain's state, is vital for assessing the environmental impact of each transfer. `addTransfer` is the contract's primary function, tasked with recording transfers on the blockchain. Figure 3 shows this function pseudocode. It creates a new Transfer object, updates the transfer history, and emits an event to confirm the transfer's registration. Its execution actively changes the blockchain's state and facilitates integration with external applications for transfer registration. `getBatchHistory` allows access to a batch of avocados' transfer history, given its latest reference ID. This function does not alter the blockchain's state but is essential for enabling external applications to query historical batch data.

```
Algorithm 1: addTransfer
Input: newBatchId, prevBatchId, batchSize, distance, transportMode
If transport data are correct then
    co2Emissions = calculateCO2Emissions (distance, batchSize, transportMode)
Else
    Error "Invalid transport mode"
End
Create newTransfer record with newBatchId, prevBatchId, batchSize, distance, transportMode, co2Emissions
If there is no history for prevBatchId then
    Initialize history for newBatchId with newTransfer record
Else
    Copy history from prevBatchId to newBatchId
    Append the newTransfer to newBatchId's history
End
Update batchIdLinks to link newBatchId with prevBatchId
Emit NewTransfer event with the transfer details
```

Figure 3 Pseudocode to add a new transfer

4. Case study

In recent years, the semiconductor supply chain has emerged as one of the most challenging topics in supply chain management. Electronics are pivotal in supporting automation, electrification, connectivity, entertainment, and security within the automotive sector. For example, Electronic Control Units (ECUs) utilise microcontrollers, which are coupled with sensors, and include connectivity modules (De Boeck, Lèquepeys & Kutter 2023). However, semiconductor-based components are facing challenges in areas such as sustainable resource management, disruptive events, and visibility issues among parties.

The globalised supply chain for a car ECU is complex and demands specialised regional expertise. It begins with the licensing of intellectual property in Europe and depends on advanced software from American companies, along with high-purity materials processed in the United States and Japan. South Korea’s expertise in wafer manufacturing, coupled with Taiwan’s advanced semiconductor foundries to fabricate the chips, dominates the middle production phases. These chips are then sent to Malaysia for packaging and testing to adhere to the automotive industry's strict standards before being assembled into circuit boards in China. Finally, the ECUs reach their destination in Europe, where they're integrated into vehicles and sold.

We suppose a journey in the last steps from tier-1 to OEM, involving multiple steps from manufacturing to final delivery, each with its own challenges and processes. For example, a production facility in Taiwan manufactures, assembles, and tests ships by truck from the manufacturing site to the nearest major export port in Taiwan, such as the Port of Kaohsiung. The shipment is then loaded onto a container ship bound for Hong Kong for further transportation arrangements. Upon arrival in Hong Kong, the shipment is unloaded and goes through import customs clearance procedures. The shipment is loaded onto a trans-Pacific container flight to New York. Upon arrival in New York, part of the shipment makes a domestic trip by truck to San Francisco. Simultaneously, another portion of the shipment leaves New York via a container ship headed for Amsterdam. The final phase of the journey sees the shipment airborne from Amsterdam to Stuttgart, Germany. Table 1 shows a detailed representation of the multimodal logistic pathway of an ECU from Tier-1 to OEM.

The project's functionality was confirmed using Ganache, part of the Truffle Suite, which delivers an extensive toolkit for blockchain development, testing, and deployment. Ganache specifically provides a private Ethereum blockchain for developers to perform commands, review network states, and monitor real-time interactions within transactions and smart contracts. The private keys and blockchain addresses used in the scripts are simulated, created by Ganache for testing purposes. To effectively execute the scripts, it's essential to replace these placeholders with actual values from Ganache's Graphical User Interface (GUI) when initialising a new blockchain. This approach allows developers to rigorously test their applications in a secure, manageable setting prior to live deployment on the Ethereum network.

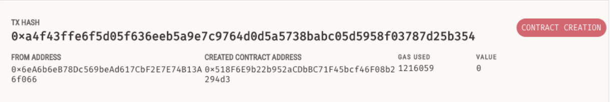
5. Results and discussion

The actual functionalities of the proposed application will be demonstrated. The test will be conducted by simulating step by step the ECU distribution chain. Firstly, the supply chain manager, with the consensus of all supply chain

Table 1 Case study: global shipment journey of an ECU lot

Source	Sink	LAT Source	LON Source	LAT Sink	LON Sink	Previous ID	Current ID	Size [kg]	Trans. Mode
Taiwan	Taiwan (Port)	24.779137	120.991945	22.618577	120.274241	TAY-UPNXR2024	TAY-ZDIYJ2024	500	Truck
Taiwan (Port)	Hong Kong	22.618577	120.274241	22.304858	114.215523	TAY-ZDIYJ2024	CHI-DFXKK2024	500	Ship
Hong Kong	New York	22.304858	114.215523	40.991530	-73.656155	CHI-DFXKK2024	USA-NAHOM2024	500	Air
New York	San Francisco	40.991530	-73.656155	37.774929	-122.419416	USA-NAHOM2024	USA-YRTOE2024	250	Truck
New York	Amsterdam	40.991530	-73.656155	52.359530	5.025779	USA-NAHOM2024	EUR-TMHKU2024	250	Ship
Amsterdam	Stuttgart	52.359530	5.025779	48.778953	9.157644	EUR-TMHKU2024	EUR-WDZKM2024	250	Air

partners, executes the contract deployer file to create the first transaction of the smart contract. The contract is now operational and is automatically assigned an address on the network (i.e., “created contract address” in Figure 4). Subsequently, the transaction will be mined and inserted into a block with its respective timestamp.

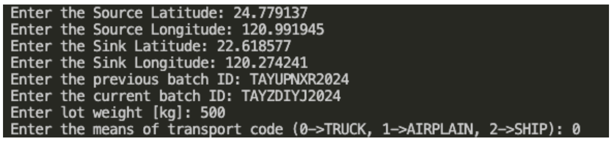


```
TX HASH
0×a4f43ffe6f5d05f636eeb5a9e7c9764d0d5a5738babc05d5958f03787d25b354          CONTRACT CREATION

FROM ADDRESS                                 CREATED CONTRACT ADDRESS                     GAS USED   VALUE
0×6eA6b6eB78Dc569beAd617CbF2E7E74B13A 0×518F6E9b22b952aCDbBC71F45bcf46F08b2 1216059    0
6f066                                        294d3
```

Figure 4 Contract creation transaction on Ganache

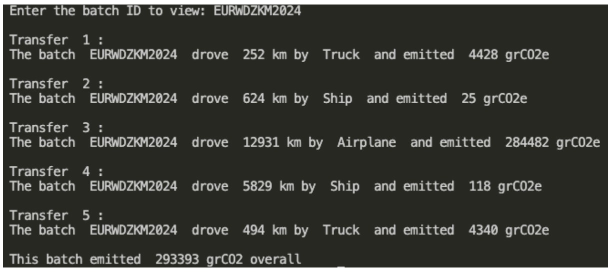
The ECU shipment journey begins with production in Taiwan. After manufacturing, the ECUs are packaged into 500 kg packs, assigned an ID ("TAY-UPNXR2024"), and shipped by truck to Taiwan's main export port. Here, the first significant transition occurs, with the ID changing to "TAY-ZDIYJ2024" to mark the shipment's readiness for international transport. Upon reaching the port in Taiwan, the shipment is loaded onto a container ship bound for Hong Kong. The pack data is scanned (via RFID or QR code), a new identifier ("CHI-DFXKK2024") is assigned, and the transfer updater file updates the blockchain accordingly (Figure 5). The procedure outlined in the previous steps is repeated for the other transfers.



```
Enter the Source Latitude: 24.779137
Enter the Source Longitude: 120.991945
Enter the Sink Latitude: 22.618577
Enter the Sink Longitude: 120.274241
Enter the previous batch ID: TAYUPNXR2024
Enter the current batch ID: TAYZDIYJ2024
Enter lot weight [kg]: 500
Enter the means of transport code (0->TRUCK, 1->AIRPLAIN, 2->SHIP): 0
```

Figure 5 Taiwan-Port transfer input

The total emissions generated by the shipment of the batch from Taiwan to Stuttgart are reported in Figure 6. The final ID associated with the batch is "EURWDZKM2024."



```
Enter the batch ID to view: EURWDZKM2024

Transfer  1 :
The batch  EURWDZKM2024  drove  252 km by  Truck  and emitted  4428 grCO2e

Transfer  2 :
The batch  EURWDZKM2024  drove  624 km by  Ship  and emitted  25 grCO2e

Transfer  3 :
The batch  EURWDZKM2024  drove  12931 km by  Airplane  and emitted  284482 grCO2e

Transfer  4 :
The batch  EURWDZKM2024  drove  5829 km by  Ship  and emitted  118 grCO2e

Transfer  5 :
The batch  EURWDZKM2024  drove  494 km by  Truck  and emitted  4340 grCO2e

This batch emitted  293393 grCO2 overall
```

Figure 6 Total emissions for EURWDZKM2024 batch

The analysis reveals that the highest environmental impact is attributed to the third journey, generating 284482 $grCO_2e$, accounting for 90% of the total. This is due to the longest stretch (96.97% of the total journey) being covered by air travel, which is significantly more polluting than other modes of transport. The proposed application can accurately perform such estimations, provided it is equipped with the correct emission coefficients for the various modes of transport used.

The blockchain system for tracking products in the supply chain provides significant advantages over existing solutions, eliminating the necessity for product owners to authorise each component of the value chain. This is particularly beneficial in complex supply chains, where supervision of subordinate manufacturers is often limited. The proposed system enables manufacturers to autonomously document sustainability information directly on the blockchain. The network concentrates on concise and relevant information for calculating the product's carbon footprint, easing the dissemination of data.

6. Conclusions

The European Union's CSRD for 2022 mandates more rigorous sustainability disclosures, including Scope 3 emissions reporting. These indirect emissions, often a significant portion of an organisation's carbon footprint, underscore the need for effective management and transparency in the supply chain. Traditional data collection methods, such as surveys, face challenges due to supply chain complexity and data-sharing reluctance among suppliers, leading to insufficient emissions reporting.

Blockchain technology emerges as a solution, offering a secure and immutable ledger for recording transactions and tracking goods. When integrated with the IoT, blockchain enhances supply chain visibility, data integrity, and stakeholder collaboration. The use of Ethereum smart contracts and DApps facilitates automated, transparent emissions reporting, allowing for direct, verified data input.

This study explores the use of blockchain to improve the tracking and reporting of Scope 3 carbon emissions across supply chains, focusing on the relationship between Tier-1 suppliers and OEMs. A system developed in Solidity and Python simplifies the analysis of a product's environmental impact from production to sale. The project particularly highlights the semiconductor supply chain and the environmental implications of global logistics, notably air transport.

Despite the promising results, the proposed study has some limitations. The current smart contract does not utilise the other two methods indicated by the GHG Protocol (i.e., fuel-based and spend-based methods). It is not integrated with sensors and user interfaces, and it does not include downstream emissions. These limitations highlight areas for further development to provide a more comprehensive and accurate carbon accounting solution. Future enhancements will include integrating fuel and spend-based methods for more accurate emissions calculations, developing a transport vehicle database, and incorporating sensor technology for automated data input. Plans also involve using spatial APIs for precise distance calculations and expanding the scope to cover more emissions categories, including downstream distribution. Additionally, an app or website interface for end-users, triggered by QR code scanning, will provide insights into the environmental impact of their purchases. Security improvements will address the risk associated with including private keys in script files, ensuring sensitive information remains protected.

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Acknowledgment

Project partially funded under the National Recovery and Resilience Plan (NRRP), Mission 04 Component 2 Investment 1.5—NextGenerationEU, Call for tender n. 3277 dated 30 December 2021. Award Number: 0001052 dated 23 June 2022.

Also, partially funded by the ESF REACT-EU: Programma Operativo Nazionale (PON) "Ricerca e Innovazione" 2014–2020, CCI2014IT16M20P005, Progetti DM 1062 del 10 August 2021.