A Distributed System for Optimization of Carbon Emitting Resource Consumption in Supply Chains

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***Abstract*—Industrialized supply chains significantly impact the environment by accelerated greenhouse gas emissions. As supply chains get complex, they suffer from fragmentation in terms of sharing knowledge among participants. Fragmented chains such as the meat business, encompasses sub-stages like feed production, processing, distribution and retail but incorporate bare minimum vertical integration. This hinders measurement of carbon footprint against products being shipped. Lack of infrastructure to estimate emissions at different independent stages results in lost opportunity to minimize emissions from end-to-end. To address issues arising from isolated supply chain participants, we propose a decentralized framework leveraging blockchain functions, internet of things, and distributed databases to allow to capture fine-grained greenhouse gas emissions across supply chain for joint optimization of underlying resource consumption. The proposed framework facilitates formation of a mix of local and global collaboration groups for precise carbon emission tracing while ensuring privacy and transparency. Key framework features include system's extensibility and scalability for integration of diverse information sources, secure data capture mechanism, and propagation of data and policies via blockchain and internet of things infrastructure. Our proposed solution aims to offer a flexible, comprehensive, and collaborative approach to recording, monitoring and optimizing carbon footprint across complex disjoint supply chains, thereby promoting improved environmental output management.**

***Index Terms*—blockchain, distributed, emissions, optimization.**

I. Introduction

Reduction of 'carbon footprint' has now become a necessity due to its importance in quantifying global warming. Tracking the 'carbon footprint' is difficult than tracking other environmental footprints (e.g. water impact) because it involves Greenhouse Gases (GHG) as well as indirect Carbon Dioxide (CO_2) contributions [1]. Industrialization has accelerated emissions and made it difficult to track it since parts of the supply chains are not directly connected and do not share required information. As a result, environmentally toxic processes in supply chains keep poisoning the surroundings unnoticed. Unless emissions from major driving forces of the economy such as the supply chains can be precisely tracked, managing them will be impossible. A first step towards tracking, managing and optimizing emissions would be to connect scattered parts of the supply chain such as production, processing, harvesting, packaging, distribution, and retail [2].

The impact of carbon footprint from any closed system is calculated using Lifecycle Assessment (LCA) [3]. LCA considers GHG's associated with materials in its raw stage up to the final disposal of a product. LCA quantifies emissions associated with resource consumption inside a closed system in relation to system output. For complex supply chains such as the meat chain involving timely processing of products, LCA encompasses carbon footprint along with Global Warming Potential (GWP) and other significant processes. Performing LCA in a complex disjoint supply chain is challenging because the only connection between participants is the 'point-of-sale'. Formally, the carbon footprint is measured in Carbon Dioxide equivalent (CO_2eq) units based on a 100-year GWP (GWP100). Gases contributing to carbon emissions include Methane (CH_4) with a GWP of 25 and Nitrous Oxide (N_2O) with a GWP of 265, reflecting a higher impact than CO_2 [4].

Due to direct emissions, the 'Beef Supply Chain' contributes a lot to climate change from cattle raising and feed production activities. Despite growing meat demand, lack of willingness to share internal resource consumption data with other organizations is a major hurdle towards global supply chain related emissions optimization. Carbon emissions optimization in disjoint chains is challenging due to the complexity of coordinating multiple stakeholders, each with their unique regulatory requirements. Using a centralized platform to gather real-time emission measures is not possible because of how the underlying emissions contributing sources are spread out.

Connecting with other organizations beyond 'point-of sale' for the sake of sharing estimates of internal emissions requires a framework, where the technology and polices should be dictated by collaborating participants. Over time, centralized and 3^{rd} party controlled solutions for collaboration has not seen success due to privacy concerns. Any acceptable solution allowing organizations to form collaboration groups therefore, needs to give participants full control over the type of technology and its way of use. A framework where users have control over the collaboration application could pave the way for transparency and traceability of emissions because of the trust it can provide. A reliable and scalable decentralised and distributed platform where organizations can independently join other organizations of choice for collaboration while having full control over their own data flow, can cater privacy concerns and vertical integration along with providing a trustworthy platform for managing emissions from 'end-to-end'.

In this paper, we propose a distributed and decentralized collaboration architecture controlled by independent organizations. Connectivity for information sharing is enabled using a privateblockchain consortium coupled with Internet of Things (IoTs), connectivity channels and distributed databases spread across different domains.The proposed framework allows organizations to form and manage independent or overlapping connected collaboration groups utilizing blockchain channels and distributed databases as needed. This facilitates secure and automated estimation of emissions from all major GHG emitting sources throughout the chain, that participants are willing to share. Unlike previous approaches that relied on central and 3rd party controlled databases, or focused on limited parts of the chain to capture emissions, our framework is the first step in building trust that could allow inter-domain knowledge transfer between supply chain participants by providing full control over collaboration group structure, underlying technology and shared data. Use of the latest open source tools provides a cheaper yet reliable and flexible solution for adapting the framework for applications that are a direct derivative of emission tracking. For example, users can collaborate to promote development of carbon sequestration policies in addition to validating and adopting environment friendly green projects.

II. Literature Review

Assessment of emissions in complex supply chains heavily make use of LCA but due to limited access to internal processes, research involving LCA in disjoint chains utilizes data from only some of the participants with less reliable assessments [5, 6]. Though LCA is effective for evaluating environmental impacts from resource utilization, it is subject to variability because of the underlying assumptions. LCA is therefore not universally applicable across systems unless there are intuitive mechanisms to gather detailed measurements [7]. To cope with the difficulty of system measurements, guidelines for GHG emissions advocated by bodies like IPCC (Intergovernmental Panel on Climate Change) are commonly used. Compared to the most relaxed fixed factor IPCC tier 1 policy, tiers 2 and 3 incorporate more details to account for variations [8]. LCA can be considered a valuable tool for measuring climate change impact from beef chain but the fragmentation among participants (e.g. between breeders and distributors) is quite challenging [9, 10]. This disconnection makes it difficult to effectively track emissions, limiting the possibility to measure precise impact from underlying processes. We use ‘Beef Chain’ as a example to highlight the need of a solution that addresses end-to-end management of emissions.

Use of LCA in beef chain for carbon footprint along with other measures (e.g. biodiversity) has been instrumental in identifying emission hot spots. Recent analyses highlights the importance of optimizing logistics and transportation to reduce emissions [6]. Sustainable agricultural practices, such as precision farming and renewable energy usage have also shown potential for emission reductions [11]. However, the fragmented nature of the beef chain complicates carbon optimization, necessitating the need for collaborative frameworks and transparent communication[12, 13]. Measuring emissions is ineffective until there is a framework on which disjoint participants can trust and allow it to pull and share internal emission estimates. Still, participants would want full control over the shared data in any form of collaboration.

Digital Ledger Technologies (DLTs) such as the blockchains have been at the forefront for enhancing tracking in supply chains. Blockchains combined with other types of DLTs offer potential for resource management decisions once all required supply chain data is available. However, challenges persist in gathering end-to-end statistics due to limitations such as reliance on central nodes, permission-less architectures, and fixed blockchain infrastructure. A fixed data management interface for sharing information between organizations is a big hurdle in overall supply chain resource management. An effective end-to-end resource management requires sharing numerous decisions and policies along with bidirectional vetting until a management strategy can be enforced [14, 15, 16, 17]. Since sharing of data, decisions, policies and vetting processes cannot be done over currently fixed ’point-of-sale’ channels between organizations, there is therefore a need for flexible architecture where different levels of data communication channels can be flexibly initiated. Blockchain in itself requires a lot of planning, specially for deployment in a distributed manner and failure to cater the needs of underlying blockchain application has been reported to cause compromise in data integrity [18]. This further necessitates a carefully studied platform around blockchain, IoTs and other DLTs to allow reliable reporting of statistics for resource optimization.

Today’s supply chains produce emissions in billions of metric tons of CO_2eq. Advances in supply chain has made current architectures complex and independent. The distributed nature of chains now heavily depends on output from other stages as input. The ‘Beef Supply Chain’ is considered a environmentally burdensome chain in terms of direct CH_4 and CO_2 emissions. The layout of beef chain incorporates numerous subsystems including feed production, harvesting, cold storage and retail management. Starting from calf rearing until sale of packaged beef, all sub-processes have their own closed loop local environment contributing to emissions. This makes it difficult to convince participants to share data.

To address challenges in collecting emissions related data for joint resource optimization globally, we implement a decentralized and distributed framework that allows creating collaborative group zones (local and global) to facilitate non-pervasive data sharing. The non-pervasive nature stems from the ability of participants to control the type of distributed services and applications being run and the data being shared. We build our application around the ‘Beef Supply Chain’ scenario because of its importance in global emissions, its complexityand the number of dispersed participants. System boundaries for our application scenario is shown in Fig 1. Our application is meant to bring together participants in supply chains with high climate impact for the purpose of collaboratively sharing data for optimizing internal functions including minimizing end-to-end carbon footprint.

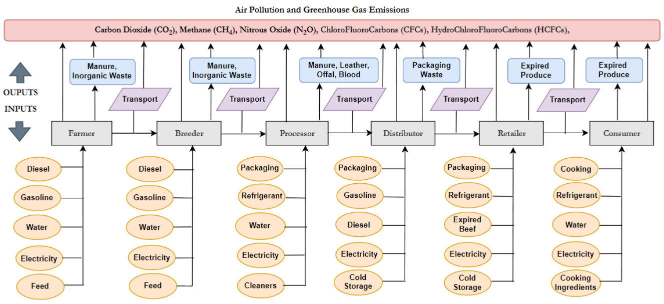


Fig. 1: System boundaries of proposed application.

III. Proposed Framework and Implementation

We implemented a connectivity framework aimed at promoting collaboration for emissions optimization in supply chains with a number of objectives. First, the application is *generic* to allow formation of groups of different sizes. Second, it is *scalable* and allows seamless integration of blockchain layer, IoTs and distributed databases to establish decentralized end-to-end connectivity of different scales. Lastly, it is *data-driven* and *reliable* in the sense that a collaboration group is formed around the need for managing and sharing specific information. A framework built upon mutual control by stake holders removes trust and transparency concerns and paves the way for running applications with mutual benefits.

A. Overview of framework

The backbone of our application is a framework around organizational approved decentralized and distributed blockchain components, private connectivity channels, databases, and interface for IoTs as shown in Fig. 2. The frameworks structural form depends on the participants (e.g. farmers, breeders and abattoirs) requirements. The data connectivity channels help in routing group tasks, finalizing policies, vetting members, sharing data and managing supply chain information. Since the blockchain ledger in itself is not suitable for storing large data files, distributed and local databases are setup during the group creation. Distributed database includes IPFS (InterPlanetary File System) while local databases include SQL and NoSQL databases. In our framework, an 'organization' is a chain participant with distinct goals, a 'consortium' denotes a collection of organizations with shared objectives. Once a collaboration group is functional, participants mutually log emission-related data on shared databases. References to off-chain distributed data (on IPFS) is also stored in blockchain. In short, the framework facilitates sharing knowledge for informed emissions related decisions and supply chain resource optimization by establishing communication channels over participant configured interfaces with back end connection to resources such as databases, IoTs and sensors.

B. Initializing and creating groups

To begin with, an emissions group coordinating server application is deployed to facilitate group formation by coordinating resources that each group can utilize (as show in Fig. 3(a)). The secure resources mutually created, managed and shared between group members include information about vetted group organizations, addresses required to configure shared network drives and mutual databases along with data communication channels. The database of group resources, managed by a RESTful flask application, can be modified to include any type of information, e.g. files, containerized applications, database entries. The group coordinator service is also available in a containerized form within each groups resource so that members can communicate by initializing their own coordinating servers. Nevertheless, once a group is formed with required number of organizations, channels, networks, database and IoTs, it does not need coordinator for operations. At any point in time, a trusted organization in a group can be mutually tasked with taking the role of a coordinator in addition to their own group activities.

The coordinator (also termed collaborator/initiator) along with pooling group resources, also starts a blockchain network. The blockchain network provides a consortium group for members to connect to and expand from. Once members set up the blockchain services (blockchain sequence orderer node, Certificate Authority (CA), channels and databases) by expanding from the coordinator end, they can mutually restructure the group consortium as it expands. Resources are distributed through in the form of lightweight containerized applications ('yaml' files). A default global blockchain 'emissions-channel' runs at the coordinator serving multiple functions. First, it serves as a regulatory channel for managing traceability data. Second, it provides a secure ledger timeline for group activities. Third, it facilitates coordinating global policies, actions and information for optimizing emissions. Groups at their own end start inter-organization blockchain channels (e.g. farmer-breeder-channel) as shown in Fig 2.

C. Micro-services running at organization level

All group related services running within organizations securely expose APIs (Application Programming Interfaces) using custom scripts for managing different functions (e.g., starting IPFS networking and uploading/downloading data). The CA application facilitates secure member access to group services. Scrutiny of new members is done based on vetting process by members or verifying identification numbers on database. In short, services that each organization starts to enable emissions tracking and optimization utilize configured (overlay and bridge) networks, reachable (IP) addresses for private IPFS database, and routing information for applications like network shared drive (using GlusterFS). Blockchain network and services in our framework are configured using custom scripts and open source Hyperledger Fabric (2.5) tool.

Organizations in a collaboration group locally deploy IoT and sensor-related container services as part of the emissions application framework. This is accompanied by setting up channels attached to sensor interfaces for taking in (consuming) data. The IoT application is setup using open source Mainflux software with custom scripts. Since we focus on 'Beef Supply Chain', sensors are configured to gather specific beef chain data. A list of category (from literature) for organizational resources consumed in our deployed application

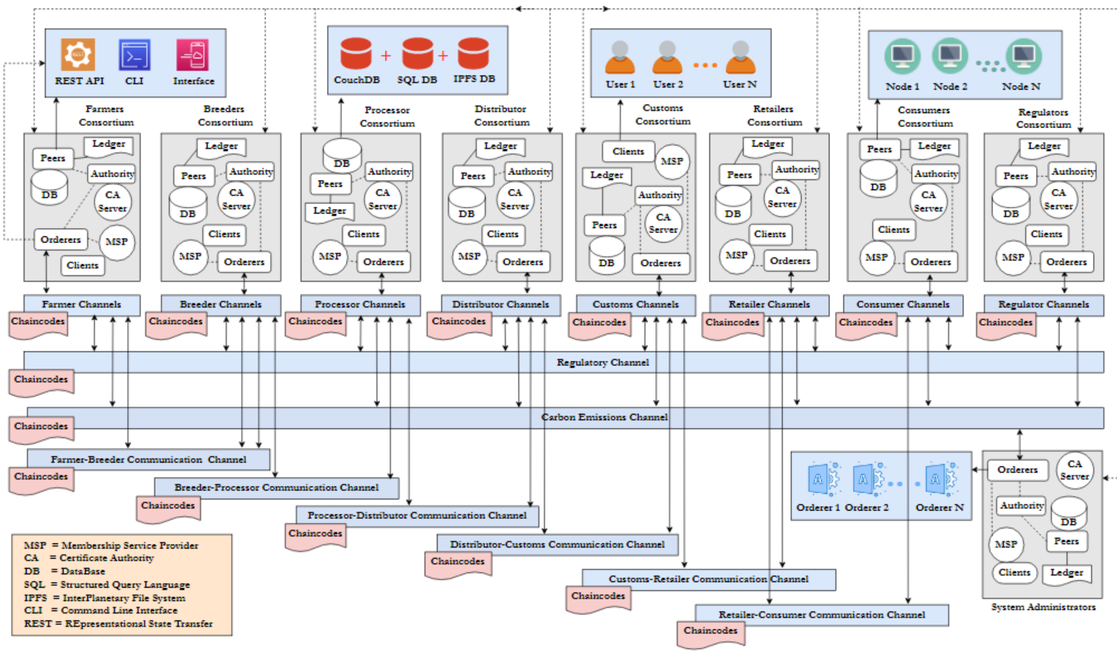
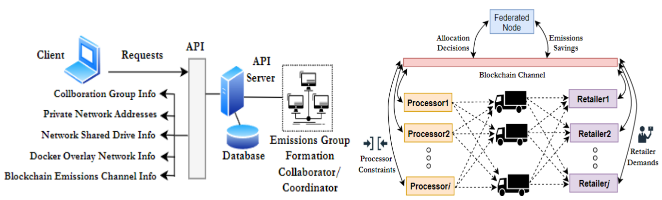


Fig. 2: An overview of connectivity framework for collaborative emissions tracking and optimization.



(a) coordinator setup (b) decision routing

Fig. 3: (a) An initialization server facilitates the first phase of creating a consortium. Finalized groups takes off, disconnect from root and optionally set up their own coordinators (b) decision of optimal paths using blockchain channels.

and possible emissions (IPCC tier 2/3) generated against them is summarized in Table I. The emission factors are mutually maintained for a group in a RESTful flask application running at one of the organizations in a group or as a 3^{rd} party NGO node. Users send requests with resource consumed at their to get a response with total emissions in metric tons CO_2eq. Using the emissions factor management service, local (e.g. in Iowa State) or global (e.g. USA-Canada) emission zones are created for managing emissions.

D. Enabling carbon emissions optimization application

Carbon emissions tracking and optimization is enabled by gathering resource consumption data from IoT applications running at each member organization. The resource consumption data (e.g. total electricity at the end of period) used (as shown in Table I) are non-sensitive information that do not expose underlying details. As animals move from in the chain, emissions data is recorded in private and public digital ledgers (blockchain channels) as agreed by group members. In our application, public data allows consumers and regulators to view a summary of emissions per pound (lb) of beef in metric tons CO_2eq. Use of distributed databases allows maintaining a traceable and immutable timeline sequence of emissions. The Content Identifiers (CIDs) from data on IPFS are stored in blockchain providing a one-to-one mapping for extra verification. Organizations run local (SQL and NoSQL databases) to create a data pipeline for managing raw data and filtering it for sharing with members.

Together with the combination of IoT services, blockchain channels, distributed and local databases, emissions are recorded for different processes (e.g. energy consumption). With the distributed nature of the framework, local information (e.g. internal process details) is kept within organization and global information is securely shared between members. A lightweight 'GO' language-based program is installed on blockchain channels allowing members to manage data consistently along with support for native operations like reading, writing, updating and deleting records with different formats. With a single run of emissions calculation from end-to-end, a group can synthesize a reference framework for estimating possible future emissions when a different set of animals pass through the chain. This generates the possibility of optimizing the chain for lesser emissions before hand by creating specific routes for animals depending on demand and supply along with creating suggestions for greener methods. Optimization calculations and decisions are performed by incorporating a mutually managed 3rd party organization (scientific application node) in the group using same micro-services (IPFS, blockchain, distributed database) and additionally running optimization algorithms on demand and supply datasets with constraints pulled from emissions reference framework for a particular group (as shown in Fig 3(b)).

TABLE I: Emission category for CO_2eq taken from literature.

Category	Emission Source	Unit Used	Ref
Energy	Electricity	kWh	[19]
	Diesel	lb	[19]
	Fossil	lb	[19]
	Gasoline	lb	[19]
	Natural Gas	f^3	[19]
	Steam	lb	[20]
	Solar	kWh	[21]
	Wind Turbine	kWh	[22]
Feed	Alfalfa Hay	lb	[23]
	Grain	lb	[24]
	Corn/Maize	lb	[23]
	Milk-Replacer	lb	[25]
	Soybean	lb	[23]
	Mineral Mix	lb	[23]
	Protein Mix	lb	[25]
	Grass Hay	lb	[23]
	Byproduct	lb	[25]
	Seeds	lb	[26]
	Barley	lb	[27]
	Oats	lb	[27]
	Wheat	lb	[27]
	Rye	lb	[27]
Byproducts	Methane	lb	[28]
	Manure	lb	[29]
	Waste	lb	[25]
	Blood	gal	[30]
Packaging	Plastic	kg	[31]
	Paper	kg	[32]
	Cardboard	kg	[33]
Fertilizers	Nitrogen	lb	[34]
	Potash	lb	[34]
	Phosphate	lb	[34]
Pesticides	Fungicide	lb	[35]
	Herbicide	lb	[35]
	Insecticide	lb	[35]
Processes	Heating	kWh	[36]
	Cooling	kWh	[36]
	Electro-Chemical	kWh	[37]
Cleaners	Cattle-**Cleaner**	lb	[38]
	Facility-**Cleaner**	lb	[39]
	Groundwater	Gal	[40]
	Brackish Water	Gal	[40]
	Desalinated Water	Gal	[40]
	Recycled **Water**	Gal	[40]
Machinery	Pumps	kWh	[19]
	Fans	kWh	[19]
	Site Transport	lb	[19]
	Materials Handling	kWh	[19]
	Compressed **Air**	kWh	[19]
	Electronics	kWh	[19]

IV. Results and Discussion

A 'Beef Supply Chain' specific scenario is set up by coordinating through a group initiator server to demonstrate emission tracking and optimization. A collaboration group comprising of breeder, processor (abattoir), distributor, retailer and an emissions management and optimization organization (scientific node) is setup. Due to resource restrictions (number of physical machines with unique IP addresses) and for demonstration purposes, we set up the organizations in such a way that they can be forked to represent more than one organization for illustrating a setup of hundreds of participants. Specifically we set up 3 nodes of each organization (breeder, processor, distributor, retailer) and use multiple blockchain channels (e.g. breeder-channel-N) to represent different participating organizations. When the optimization problem becomes complex (e.g. requiring hundreds of breeders), we further reconfigure blockchain channels to represent more than one organization by re-using underlying variables defined by the program installed on channel. This stems from our limitation to arrange and manage hundreds of VMs (physical machines) at one place at a time or to buy costly VM instances on cloud. In practice however, a lightweight VM is enough to run all services intended to be run at each organization (blockchain node, IPFS, databases and IoT services). Each VM used in experiments utilizes Linux (Ubuntu 22.04) with at least 6GB of RAM and 40GB of hard disk. This configuration can be deployed both on cloud platforms and locally, with each organization managing its own local setup of containers.

The carbon optimization (reduction) problem in our example is defined as a federated machine learning decision process (as shown in Fig 3(b)). A set of distributed nodes (a group) representing source and destination organizations decide on which routes for animals to send that would minimize emissions. The set of possible choices from which each organization can decide a route, is sent to optimizer node. Optimizer node maintains a reference framework (total possible emissions for each route) by making use of resource consumption (using Table I) and their outward emissions for each organization in the path (in metric tonnes of CO_2eq per lb of beef). The optimizer node forms a linear programming model from presented choices and runs linear optimization programs over it until an solution is found. Decisions are then sent to requesting nodes. Take the case of a number of processors trying to decide which retailers should be chosen. The carbon emissions cost matrix C_{ij} represents emissions cost incurred when beef is shipped from processor i to retailer j. Emissions cost takes into consideration the resources consumed for the travel distance between processor and retailer (as shown in Fig 5). Emissions cost can be directly converted to financial costs, resulting in possible savings. Consider each retailer with a demand of beef quantity which can be expressed as D_{R_i} while each processor has a limit of beef production during the specified time (S_{P_j}). The decision variables can be defined as X_{ij} where X_{11} represents amount of beef that can be delivered from processor 1 to retailer 1, X_{12} represents amount of beef that can be delivered from processor 1 to retailer 2 and so on. Objective function then takes the form:

$$Minimize(\sum_{i=1}^{n}\sum_{j=1}^{m} C_{ij} * X_{ij}) \tag{1}$$

subject to processor and retailer constraints

Here, main objective is to choose quantity of beef that can be supplied from a processor to a retailer while minimizing overall carbon emissions across all suppliers and retailers. Optimization problem is therefore the sum product of carbon emissions cost matrix and the allocation matrix. Each carbon cost entry (c_{ij}) in the cost matrix is an aggregation of resultant carbon emissions from all resources consumed when a given amount of beef is processed and shipped. Carbon cost entry in the cost matrix can therefore be defined as:

$$\begin{aligned} c_{ij} = c_{energy} + c_{feed} + c_{byproducts} + c_{packaging} + c_{fertilizers} \\ c_{pesticides} + c_{processes} + c_{cleaners} + c_{machinery} \\ -c_{plantation} - c_{sequestration} \end{aligned} \tag{2}$$

The constraints for objective function are defined in terms of total capacity of processors supply across all retailers and the retailers total demand across all processors. The processor constraint can be defined as:

$$\begin{aligned} X_{11} + X_{12} + X_{13} + X_{14} + ... + X_{1j} <= T_{p_1} \\ X_{21} + X_{22} + X_{23} + X_{24} + ... + X_{2j} <= T_{p_2} \\ X_{31} + X_{32} + X_{33} + X_{34} + ... + X_{3j} <= T_{p_3} \\ \vdots \\ X_{i1} + X_{i2} + X_{i3} + X_{i4} + ... + X_{ij} <= T_{p_i} \end{aligned} \tag{3}$$

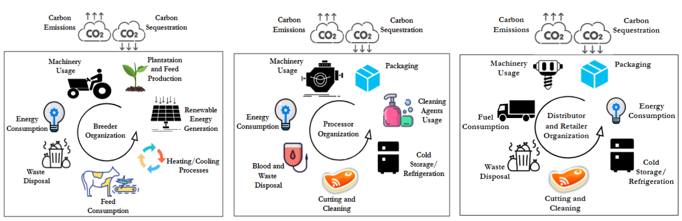
Processor related constraints in essence highlight that the total allotment of beef by weight done across all retailers for a given processor or $i-th$ abattoir cannot be more that the capacity of the processor/abattoir. Retailer constraints are:

$$\begin{aligned} X_{11} + X_{21} + X_{31} + X_{41} + ... + X_{i1} >= T_{R_1} \\ \\ X_{12} + X_{22} + X_{32} + X_{42} + ... + X_{i2} >= T_{R_2} \\ X_{13} + X_{23} + X_{33} + X_{43} + ... + X_{i3} >= T_{R_3} \\ \vdots \\ X_{1j} + X_{2j} + X_{3j} + X_{4j} + ... + X_{ij} >= T_{R_j} \end{aligned} \tag{4}$$

where the constraints above define the total allotment of beef by weight to each retailer or the $j-th$ retailer variable should be set such that the retailers demand is met. For practical reasons, decision variables only take positive integer values. The decision variable related allocation matrix is then:

$$\begin{aligned} &[\,[\,X_{11}\ X_{12}\ X_{13}\ X_{14}\ ...\ X_{1j}\,] \\ &\ [\,X_{21}\ X_{22}\ X_{23}\ X_{24}\ ...\ X_{2j}\,] \\ &\qquad\qquad \vdots \\ &[\,X_{i1}\ \ X_{i2}\ \ X_{i3}\ \ X_{i4}\ ...\ X_{ij}\,]\,] \end{aligned} \tag{5}$$

For demonstration of our framework's usefulness, we present a number of optimization problems. The optimizer node gathers data and sends back decisions to requesting pair of nodes through blockchain channels. Defined problems involve minimizing carbon emission costs between (i) Breeder-Processor (ii) Breeder-Distributor (iii) Breeder-Retailer (iv) Processor-Distributor (v) Processor-Retailer and (vi) Distributor-Retailer. Each problem requires possible resource consumption estimates (reference) between multiple source and destination pairs before the actual carbon emission cost matrices can be utilized. With a linear trend of resource consumption and emissions output, minimizing carbon emissions results in minimizing resource consumption with possible savings. Optimization problems at the optimizer node is solved by utilizing open source PuLP library. PuLP supports a number of solvers, including the CPLEX, CBC and GUROBI solvers, which we employed in our computations.



(a) breeder (b) processor (c) retailer

Fig. 4: Major emission sources in different organizations.

To begin with, a simplified example of 6 organizations (2 processors, 4 retailers) is presented first. Excluding carbon emissions at processors, the target is to finalize a joint decision for allocation of resources such that retailers demands are met within processors constraints. Without taking into account emissions from processors, the emissions for supplying beef from processors to retailers are a direct result of using packaging materials (plastic, cardboard an paper), cooling process and use of fuel (gasoline, diesel) for transportation (as shown in Fig 4). Considering emission factors, major contributing in emissions here comes from fuel which is directly proportional to the distance between processor and retailer. In the example, processor constraints (P_i), retailer demands (R_j) and emissions cost matrix (C_{ij}) are:

$$P_i = \begin{bmatrix} p_1 & p_2 \end{bmatrix} = \begin{bmatrix} 16052.6 & 15986.4 \end{bmatrix} \tag{6}$$

$$\begin{aligned} R_j &= \begin{bmatrix} r_1 & r_2 & r_3 & r_4 \end{bmatrix} \\ &= \begin{bmatrix} 6060.1 & 7456.6 & 5158.7 & 5042 \end{bmatrix} \end{aligned} \tag{7}$$

$$\begin{aligned} C_{ij} &= \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \end{bmatrix} \\ &= \begin{bmatrix} 12.93 & 4.87 & 8.38 & 6.93 \\ 10.54 & 11.75 & 14.02 & 10.87 \end{bmatrix} \end{aligned} \tag{8}$$

where i represents processor and j represents retailer and $c_{ij} = c_{energy} + c_{packaging} + c_{processes}$. Each individual cost variable from the above equation can be expanded as an aggregation of emissions as following:

$$\begin{aligned} c_{11} &= 12.632 + 0.0387 + 0.259 \approx 12.93\ CO_2eq \\ c_{12} &= 4.76 + 0.015 + 0.097 \approx 4.87\ CO_2eq \\ c_{13} &= 8.19 + 0.025 + 0.167 \approx 8.38\ CO_2eq \\ c_{14} &= 6.77 + 0.02 + 0.14 \approx 6.93\ CO_2eq \\ c_{21} &= 10.30 + 0.031 + 0.21 \approx 10.54\ CO_2eq \\ c_{22} &= 11.48 + 0.035 + 0.23 \approx 11.75\ CO_2eq \\ c_{23} &= 13.70 + 0.042 + 0.28 \approx 14.02\ CO_2eq \\ c_{24} &= 10.62 + 0.033 + 0.22 \approx 10.87\ CO_2eq \\ \text{where,} &\quad c_{ij} = c_{energy} + c_{packaging} + c_{processes} \end{aligned} \tag{9}$$

Each individual carbon emissions cost variable can be converted to financial costs and vice versa for any organization. For example, carbon emissions cost for processor 1 and retailer 1, $c_{11} = 12.632 + 0.0387 + 0.259$ represent financial costs incurred on fuel, packaging and cooling as follows. Considering, a truck using 6000 lb of gasoline produces 6.37 CO_2eq, a distributor generating 12.632 CO_2eq from gasoline will use 11898 lb of gasoline which is \$3566 considering \$2.5 per gallon. With an average truck traveling 2100 miles on 6000 lb of gasoline (approximately 3 miles per gallon), total distance traveled would be 4161 miles which is the second longest distance in our example. Considering 700KWh produces 0.133 CO_2eq of emissions, 0.259 CO_2eq emissions would equate to 1363.11 KWh. With an average cost of 20 cents per KWh of energy use, 1363.11 KWh would equate to \$27.3. Considering 20-40-40% emissions from paper, cardboard and plastic, 0.0387 CO_2eq of packaging emissions can be broken down into 0.0155 CO_2eq from use of cardboard, 0.0155 CO_2eq from plastic and 0.0077 CO_2eq from paper. With 6kg of plastic producing 0.01 CO_2eq of emissions, 0.0155 CO_2eq of emissions equate to 9.3kg of plastic. With per kg cost of \$0.5, 9.3kg of plastic would cost \$4.65. With 12kg of cardboard producing 0.0113 CO_2eq of emissions, 0.0155 CO_2eq of emissions equate to 16.46kg of cardboard. With per lb cost of \$0.1, 16.46kg of cardboard would cost \$3.63. With 5kg of paper producing 0.0047 CO_2eq of emissions, 0.0077 CO_2eq of emissions equate to 8.19kg of paper. With per kg cost of \$0.9, 8.19kg of paper would cost \$7.91. Hence, total financial cost associated with the carbon emissions cost for c_{11} would be: $f_{11} = 3566 + 4.65 + 3.63 + 7.91 + 27.3 = \$3599.5$.

Consider the example of 6 organizations described earlier. Given carbon emissions cost matrix, the resource allocation matrix with decision variables is:

$$\begin{aligned} &[\,[\,X_{11}\ X_{12}\ X_{13}\ X_{14}\,] \\ &\ [\,X_{21}\ X_{22}\ X_{23}\ X_{24}\,]\,] \end{aligned} \tag{10}$$

TABLE II: Linear optimization problems are formulated between Breeder-Processor, Breeder-Distributor, Breeder-Retailer, Processor-Distributor, Processor-Retailer and Distributor-Retailer. Each problem consists of a supply matrix consisting of maximum amount of beef in pounds (lbs) that can be supplied from the destination and a demand matrix that represents the required amount of beef in pounds (lbs) at the source. The supply and demand matrix properties are reported for beef quantity in pounds (lbs). The carbon cost matrix properties are reported for carbon emissions in metric tonnes of CO_2eq. The objective value for optimization algorithm is reported in quantity of beef in pounds (lbs). The total decision variables are the sum of assigned variables and the ones that are not assigned.

Source	Sink	Total (i)	Total (j)	Supply Matrix (i x j)			Demand Matrix (j x i)			Carbon Cost Matrix (i x j)			Objective	Decision Variables	
		Sources	Sinks	mean	median	st. dev.	mean	median	st. dev.	mean	median	st. dev.	Value	Assigned	Not Used
Breeder	Processor	30	50	23490.06	21292.75	10188.31	8055.68	7366.3	2276.99	5491.47	5473.22	1430.17	1280253910.04	59	1441
Breeder	Processor	100	200	23811.50	23500.4	8280.4	9042.649	9141.9	2270.09	5493.87	9042.649	1442.07	2813051956.04	124	4876
Breeder	Processor	300	500	24925.98	24422.94	8591.33	9000.02	9096.90	2279.79	5501.26	5504.47	1441.98	13587691271.41	608	149392
Breeder	Distributor	30	50	35756.50	34682.60	8145.69	10786.43	10647.6	2339.71	8589.07	8595.94	1967.09	2855380690.65	51	1449
Breeder	Distributor	100	200	34142.03	32998.75	8273.56	10955.40	11138.05	2262.13	8494.70	8479.43	2014.61	11109356795.25	232	19768
Breeder	Distributor	300	500	35177.19	35033.39	8865.77	10995.55	11005.6	2293.27	8506.71	8505.25	2020.31	27628542918.33	564	149436
Breeder	Retailer	30	50	29260.83	29550.0	6454.88	12400.45	12299.4	1324.63	6550.42	6566.02	1449.21	2603315818.27	65	1435
Breeder	Retailer	100	200	29523.92	29826.25	5686.11	12586.97	12608.55	1495.45	6513.15	6546.71	1440.60	10218366212.98	266	19734
Breeder	Retailer	300	500	29939.36	29577.4	5701.24	12441.69	12356.85	1453.18	6501.41	6495.53	1444.75	24990253277.20	616	149384
Processor	Distributor	30	50	35416.80	35522.1	2737.91	17783.64	17963.2	1383.86	4997.86	4964.85	1148.90	2814876618.21	72	1428
Processor	Distributor	100	200	35222.81	35144.5	2649.52	17609.90	17740.55	1408.52	4998.53	4998.64	1159.60	10751186876.66	299	19701
Processor	Distributor	300	500	34978.16	34891.2	2836.43	17478.80	17520.3	1366.39	5003.39	5000.40	1154.90	26357738224.01	684	149316
Processor	Retailer	30	50	17757.84	17844.45	1626.50	7200.43	6927.55	1445.52	4454.42	4466.26	1438.02	782607354.74	60	1440
Processor	Retailer	100	200	17472.58	17226.1	1551.86	7601.64	7748.15	1446.26	4498.68	4488.10	1444.13	3122988567.11	271	19729
Processor	Retailer	300	500	17408.02	17316.9	1445.16	7543.87	7613.15	1451.33	4499.32	4494.32	1443.43	7614762168.17	633	149367
Distributor	Retailer	30	50	24566.70	24499.15	3014.47	12328.26	12108.40	1510.19	10.03	10.09	2.88	3290376.09	69	1431
Distributor	Retailer	100	200	25465.63	25704.8	2817.76	12381.48	12369.95	1439.20	10.02	10.08	2.89	12686037.67	296	19704
Distributor	Retailer	300	500	25204.84	25347.55	2875.90	12440.57	12503.95	1482.90	10.00	10.01	2.88	31345580.87	687	149313

The processor (supply) constraint are defined as:

$$X_{11} + X_{12} + X_{13} + X_{14} <= 16052.6$$
$$X_{21} + X_{22} + X_{23} + X_{24} <= 15986.4 \quad (11)$$

The retailer (demand) constraints can then be defined as:

$$X_{11} + X_{21} >= 6060.1$$
$$X_{12} + X_{22} >= 7456.6$$
$$X_{13} + X_{23} >= 5158.7$$
$$X_{14} + X_{24} >= 5042 \quad (12)$$

Carbon emissions and cost minimization is given as:

$$Minimize(12.93 * X_{11} + 4.87 * X_{12} + 8.38 * X_{13} + 6.93 * X_{14}$$
$$+10.54 * X_{21} + 11.75 * X_{22} + 14.02 * X_{23} + 10.87 * X_{24} + 0.0)$$
$$\text{subject to processor constraints (eq. 11)}$$
$$\text{subject to retailer constraints (eq. 12)}$$
$$\text{subject to,} \qquad 0 <= X_{ij}$$

TABLE III: Decision variable allocation for simplified 6 organization problem involving processor and retailers.

Decision Variable	X_{11}	X_{12}	X_{13}	X_{14}
Beef Allocation (lb)	0.0	7457.0	5159.0	3436.0
Decision Variable	X_{21}	X_{22}	X_{23}	X_{24}
Beef Allocation (lb)	6061.0	0.0	0.0	1606.0

The simplified optimization problem with 6 rows, 8 columns and 16 elements is solved using the CBC optimizer. An optimal solution is found after 4 iterations with an objective value of 184,699.6500 . With an output of 16,052 lb of beef from processor 1 and 7,667 lb of beef from processor 2, the final allocation of beef (decision variables) to be shipped to different retailers is shown in Table IV. X_{11} and X_{23} had the longest travel distance and consequently the highest carbon emissions, hence do not get selected.

A number of optimization problems are formulated for a bigger setup of organizations to demonstrate minimization of carbon emission costs between multiple source and destination pairs. Linear optimization problems are formulated between Breeder-Processor, Breeder-Distributor, Breeder-Retailer, Processor-Distributor, Processor-Retailer and Distributor-Retailer. Each problem consists of a supply matrix consisting of maximum amount of beef in pounds (lbs) that can be supplied from the destination and a demand matrix that represents the required amount of beef in pounds (lbs) at the source. The supply and demand matrix properties are reported for beef quantity in pounds (lbs). The carbon cost matrix properties are reported for carbon emissions in metric tonnes of CO_2eq. The objective value for optimization algorithm is reported in quantity of beef in pounds (lbs). The total decision variables are the sum of assigned variables and the ones that are not assigned. All carbon costs are a result of the resource consumption (from reference framework) between each source and destination pair. Carbon emissions calculations also involve the resources consumed at the source but excludes destination. Carbon emissions between Breeder-Processor, Breeder-Distributor and Breeder-Retailer pairs are a result of the use of following resources:

$$c_{ij} = c_{energy} + c_{feed} + c_{byproducts} + c_{packaging} + c_{fertilizers}$$
$$c_{pesticides} + c_{processes} + c_{cleaners} + c_{machinery} \quad (13)$$

For simplicity, instead of counting live animals, the total amount of usable beef (63% of live cattle) in pounds leaving Breeder is considered in the supply matrix. Supply from breeder organization indicates animals that are ready to leave for processing (abattoir). A processor sink indicates amount of beef (carcass) that can be extracted from animals while a processor source indicates amount of beef that can be supplied in packaged form to the demanding organization.

A summary of the results obtained at the optimizer node for formulated optimization problems with different source-pair sets is given in Table II. The Breeder-Distributor pair involves resources consumed at the processor while a Breeder-Retailer pair involves resources consumed at the processor and distributor. Similarly, a Processor-Retailer pair involves resource consumption at the distributor. Carbon costs estimations do not involve the use of feed, fertilizers and pesticides when breeder organization is not involved. Carbon cost matrix values fall between [3000,8000] CO_2eq with a uniform distribution for Breeder-Processor pair, between [5000,12000] CO_2eq with a uniform distribution for Breeder-Distributor pair, between [4000,9000] CO_2eq for Breeder-Retailer pair, between [3000,7000] CO_2eq with uniform distribution for Processor-Distributor pair, between [2000,7000] CO_2eq for

TABLE IV: Beef range (in lb) used for different source-destination pairs utilized in the optimization problems

Source-Destination Pair	Source Distribution Range (lbs)	Sink Distribution Range (lbs)
Breeder-Processor	(10000, 40000)	(5000,13000)
Breeder-Distributor	(20000, 50000)	(7000,15000)
Breeder-Retailer	(20000, 40000)	(10000,15000)
Processor-Distributor	(30000, 40000)	(15000,20000)
Processor-Retailer	(15000, 20000)	(5000,10000)
Distributor-Retailer	(20000, 30000)	(10000,15000)

Processor-Retailer pair and between [5,15] CO_2eq for Distributor-Retailer pair. CO_2eq emissions between distributor and retailer are the least because it only involves fuel costs and cooling process during transportation. Similarly, beef supply and demand matrix values (in lbs) fall between different ranges in a uniform distribution for different source-destination pairs summarized in Table IV. After the optimization results are obtained, decisions are routed through the framework over the established blockchain channels (as shown in Fig 3(b)).

V. Conclusion

The environmental impact of supply chains is substantial, contributing to accelerated carbon emissions. As supply chains become more intricate, they experience fragmentation, particularly in sharing knowledge between organizations. This fragmentation is evident in industrialized supply chains, which involve multiple sub-stages with minimum vertical integration. This hinders the accurate tracing and measurement of end-to-end carbon footprint. The lack of infrastructure to estimate emissions at different privately-owned, independent stages results in missed opportunities to jointly optimize emissions. To address this issue, we proposed a decentralized framework utilizing blockchain, IoTs, and distributed databases. This framework enables the capture of detailed greenhouse gas emissions across the supply chain, facilitating optimization of resource consumption. Through formation of secure and scalable privacy-preserving collaborative groups, carbon emitting resources are tracked and jointly optimized with decisions, policies and greener environment management practices mutually enforced. An example using the 'Beef Supply Chain' is presented to demonstrate the usefulness of the framework.

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