Proceedings of the 8th European Conference on Industrial Engineering and Operations Management
Paris, France, July 2-4, 2025

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/EU08.20250346
Published: July 2, 2025

Sustainable Blockchain-enabled Cut-flower Supply Chain Design to Achieve Environmental Targets; an Integrated Mathematical Model Approach

Zahra Mohammadnazari
PhD student in Centre for Business in Society
Coventry University, Coventry, UK
zahra.mohammadnazari@coventry.ac.uk

Mahdi Bashiri
Associate professor in Centre for Business in Society
Coventry University, Coventry, UK
Mahdi.Bashir@coventry.ac.uk

David Bek
Professor of Creative Economies and Ecological Sustainability, Research Centre for Creative Economies
Coventry University, Coventry, UK
David.bek@coventry.ac.uk

Abstract

This research explores the environmental footprint of the cut-flower Supply Chain (SC), focusing on carbon emissions and waste generation. Utilizing foundtations of Life Cycle Assessment (LCA), we comprehensively analyse the entire life cycle of cut-flowers, aiming to understand and identify factors underpinning the variations observed in environmental burdens. To enhance environmental sustainability, our approach integrates Blockchain Technology (BCT) with environmental impact assessment. BCT enhances transparency and traceability, streamlining decision-making across cut-flower harvest, transportation, and storage, considering waste minimization, carbon emission reduction, and cost efficiency as objectives. Furthermore, BCT brings the promise of fairer trade by the enhancement of transparency and traceability in cut-flower SC; this is to fulfil social sustainability in this research. Positioned at the forefront of impactful contributions, this study employs advanced data analysis techniques and blockchain technology. It not only provides comprehensive insights into the current state of the cut-flower industry but also proposes innovative solutions for sustainability. We have presented the mathematical model that helps with integration of BCT into assessmnet of cut flower life cycle. The results are analyzed through a numerical exmaple and insights are extracted in the end. The model successfully integrates production, transportation, and freshness considerations while selectively adopting blockchain to enhance traceability without unnecessary cost burdens.

Keywords
Sustainability, Block Chain Technology, Cut-flower supply chain, environmental impact.

1. Introduction and Literature review
The cut-flower supply chain is a complex network of interlinked stages encompassing the production, processing, distribution, and consumption of cut flowers for decorative purposes. It involves various activities such as cultivation, harvesting, post-harvest treatments, packaging, transportation, and retailing, with the ultimate goal of presenting cut flowers to end consumers. This supply chain incorporates multiple stakeholders, including flower cultivators, wholesalers, retailers, logistics providers, and consumers, all collaborating to ensure the efficient movement of cut flowers from their origin to final utilization (Reisch, Eberle, & Lorek, 2013).

Flower waste, consisting of discarded flowers from various sources, poses significant environmental challenges. Improper disposal of flower waste can lead to soil and water pollution, among other issues. Effective management and utilization of flower waste are essential for sustainable environmental practices. Flower waste can be categorized into several sources: religious and cultural ceremonies, where millions of tons of flowers are offered in temples, mosques, churches, and other places of worship and later discarded (Dey, Veerendra, Padavala, & Manoj, 2023); festivals and events, including weddings, birthdays, funerals, and celebrations like Diwali, Christmas, and Hanukkah, which often result in significant flower waste; the commercial floral industry, including florists, flower markets, and online flower delivery services, which generates substantial flower waste from unsold, damaged, or unused flowers (Chauhan et al., 2024); individual households, which contribute to flower waste through the disposal of flowers used in daily worship, home decorations, and personal gardens (Reddy & Sirisha, 2024); public spaces and parks, where the maintenance of public gardens, parks, and green spaces involves the regular trimming and replacement of flowers; and agricultural waste, resulting from the cultivation and harvesting of flowers for commercial purposes, which includes leaves, stems, and unsellable flowers (Hasna, Rafeekher, Priyakumari, & Reshmi, 2024).

Cut-flower life cycle assessment (LCA) is a comprehensive methodology used to systematically evaluate the environmental impacts associated with cut-flowers throughout their entire life cycle. It considers various stages, starting from the cultivation of flowers, through processes like harvesting, transportation, and retailing, to their ultimate disposal. By analyzing the environmental burdens and resource consumption at each stage, LCA provides a holistic perspective on the environmental footprint of cut flowers. It aids in identifying areas of environmental concern and supports the development of strategies to enhance the sustainability of the cut-flower supply chain (Kulak, Graves, & Chatterton, 2013; Lan, Tam, Xing, Datt, & Chan, 2022). Technology can streamline the management of the diverse origins and uses of fresh flowers by leveraging data analytics and supply chain management software. These tools can track the origins, destinations, and purposes of flowers, ensuring efficient allocation according to demand. Additionally, e-commerce platforms can facilitate direct sales from growers to consumers, increasing market reach and optimizing inventory management. For instance, online marketplaces and apps can connect florists and customers, enabling real-time updates on flower availability and customization options for specific uses, such as weddings or religious ceremonies. The complexities of supply chain management (SCM) in floristry can be managed with advanced technologies like blockchain, Internet of Things (IoT), and artificial intelligence (AI) (Wamba, Akter, Edwards, Chopin, & Gnanzou, 2015; Wang, Gunasekaran, Ngai, & Papadopoulos, 2016). Blockchain can provide transparent and immutable records of transactions, improving trust and traceability from farm to vase. IoT devices, such as sensors and smart tags, can monitor environmental conditions during transportation and storage, ensuring optimal flower care.

Technology can streamline the management of the diverse origins and uses of fresh flowers by leveraging data analytics and supply chain management software. These tools can track the origins, destinations, and purposes of flowers, ensuring efficient allocation according to demand. Additionally, e-commerce platforms can facilitate direct sales from growers to consumers, increasing market reach and optimizing inventory management. For instance, online marketplaces and apps can connect florists and customers, enabling real-time updates on flower availability and customization options for specific uses, such as weddings or religious ceremonies (Breiner, 2007). The complexities of supply chain management (SCM) in floristry can be managed with advanced technologies like blockchain, Internet of Things (IoT), and artificial intelligence (AI) (Wamba et al., 2015; Wang et al., 2016). Blockchain can provide transparent and immutable records of transactions, improving trust and traceability from farm to vase. IoT devices, such as sensors and smart tags, can monitor environmental conditions during transportation and storage, ensuring optimal flower care (Babich & Hilary, 2020).

This study seeks to understand the significance and the need for the technological shift in cut-flower supply chain by applying the Optimization model to elucidate the receptiveness of this industry to such technological advancements and to identify the benefits that might result from technological upgrades. It also provides the rationale for adoption of blockchain as a start of the art technology that addresses significant challenges faced by the obstacles in the industry. Hence, our work introduces a method to offer value to consumers through supply chain data and to capitalize on that data. This involves introducing a new category of data-enabled approach that cater to a growing consumer segment seeking reliable product sourcing information. To demonstrate the benefits of our proposed methodology, we present an OR-centred model around the global supply chain of fresh-cut flowers. The results underscore the value of strategically embedding BCT across the supply chain network for both consumers and supply chain stakeholders. In summary, this research examines its environmental impact, focusing on carbon emissions and waste generation, using integration with Blockchain Technology (BCT) for transparency and traceability.

2. Methodology

This research and the mathematical model it deploys, incorporate agility considerations into the modelling of blockchain technology (BCT) within the cut flower supply chain, focusing on enhancing the supply chain's responsiveness, flexibility, and adaptability. The model leverages blockchain to provide real-time data transparency, enabling dynamic decision-making across various stages of the supply chain. By incorporating real-time information on freshness, transportation modes, and inventory levels, the model facilitates rapid adjustments in response to changes in demand or supply, a key aspect of agility. This integration of blockchain data empowers the model to optimize routing, reduce waste, and maintain product quality, all of which are critical for an agile supply chain.

It is important to note that, the collaborative nature of blockchain technology enhances the supply chain's adaptability by improving coordination between suppliers, distributors, and retailers. This enables the model to quickly adapt to new supply chain configurations or partnerships, aligning supply with demand more effectively. While the model already demonstrates significant agility, further enhancements, such as incorporating scenario-based flexibility and mechanisms to respond to external shocks, would strengthen its ability to handle unforeseen disruptions, thereby fully aligning with the principles of an agile supply chain.

In this modelling we incorporate and adapt the economic theory for elasticity of demand. This theory measures how responsive demand is to changes in price - as the demand increases, the price decreases and vice versa (Acuna-Agost, Thomas, & Lhéritier, 2023). By knowing price elasticity we can draw the formulation which links demand to the price.

$$\text{Elasticity} = \frac{percentage\ of\ change\ in\ demand}{percentage\ of\ change\ in\ price} \tag{1}$$

Instead of price being dependent solely on demand, in our model it reacts to a variety of factors, making the model more realistic and applicable to real-world situations where price depends on marketing, quality, and other efforts. Higher marketing expenditures typically help to increase visibility or attractiveness of the product, which may allow the company to raise the price (Jin, Zhang, & Xu, 2017).

This model takes a whole supply chain perspective, starting with the journey that the cut-flower undergoes from production farms to distribution centres, it eventually reaches customer zones (flower shops) via various vehicle types. The freshness of the product, determined by its age since production, influences its sale price, with products aging during transportation between supply chain stages. Transportation methods vary in cost and time, impacting the freshness level of the product. We limit freshness levels to a few discrete categories. Blockchain technology can be integrated at specific points in the supply chain to track product age, with non-blockchain tracking representing the worst-case scenario. Flower shops demand depends on quality and price. Our model examines the influence of blockchain adoption on network design, treating adoption as a binary choice for tracking travel time information, wholesale receipt time and production commitments. Blockchain incurs a cost tied to the number of certified items. Adoption decisions are also considered at wholesale zones and production stages. Refrigeration costs are factored in to meet sustainability standards, aiming to reduce product wastage, particularly with blockchain adoption. Greenhouse gas emissions, including N2O, CH4, and CO2, are included in the objective function to address environmental concerns. The decision to adopt blockchain affects product quality and waste in our model. The water consumption in the production stage of cut-flowers is also factored in as an environmental impact. This would also guarantee the sustainable practice in the first stage of supply chain. The generated waste has also been tackled with in this modelling. The model minimises the waste in the transportation, production and wholesale (distribution) stage. This act is tightly linked with the decision of having the BCT or not implementing that in the SC. By the implementation of BCT, the generated waste and tracking of it could be facilitated, hence, the costing would differ (Xu, Zhao, & Liu, 2020).

Assumptions

There are several assumptions which have been built into this model; First, the model assumes that the supply chain can be divided into distinct stages, including production farm (i), wholesale (distribution) sites (j), customer zones- flower shops (k), and vehicle types (l) with varying freshness levels (f). This model is presented for a single product supply chain, but has the capacity to contain more than one product. These are represented as sets to allow for the optimization of decision variables such as production quantities, transportation flows, and freshness of products as they move through the supply chain. We considered the transportation between production farms and distribution sites as well as the transportation between distribution sites and flower shops. There are certain routes which are active between production farm (i) and flower wholesale/distribution sites (j), however, the links between flower wholesale/distribution sites (j) and customer zones- flower shops (k) are all active.

Second, the model operates under the assumption that blockchain usage incurs a unit cost (Γ) but offers several benefits, including the ability to store and share real-time data about product conditions and transport times, thus improving decision-making. The model also assumes that loss costs at both production and distribution sites are influenced by whether BCT has been adopted, with lower loss costs when BCT is used.

We also have considered transportation loss. transportation loss refers to the percentage of product spoilage or degradation occurring during transit between facilities, such as production farms, distribution centers, and flower shops. This loss arises from factors such as delays, improper handling, and unfavourable transportation conditions like temperature fluctuations. Flowers, being highly perishable, are particularly susceptible to quality deterioration over extended transit times or under suboptimal conditions. The inclusion of transportation loss in the model allows for the quantification and optimization of this risk, ensuring that waste is minimized and product freshness is preserved. By modelling transportation loss, the system can make informed decisions about routing, vehicle selection, and refrigeration needs, ultimately reducing waste, improving supply chain efficiency, and delivering higher-quality products to customers. This consideration aligns with the model's broader goals of enhancing sustainability, reducing greenhouse gas emissions, and minimizing overall costs in the supply chain.

We have taken the environmental sustainability into account in the model design by considering Greenhouse Gas Emissions (N2O, CH4, CO2). In the context of this model, Global Warming Potential (GWP) is used as a key metric to quantify the environmental impact of greenhouse gas emissions across the supply chain. GWP provides a standardized measure to compare the warming effects of different gases, such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), over a 100-year time horizon.

A key assumption involves product aging and freshness. The model assumes that product age is affected by both transportation time and storage time, with maximum allowable ages for different freshness levels. Blockchain is assumed to provide more accurate and timely data on freshness, which enables better management of product flows and minimizes the likelihood of spoilage. In the model, flower age is treated as a continuous variable, representing the time elapsed since the flowers were harvested. This variable plays a critical role in assessing the freshness and quality of flowers at various stages of the supply chain. Flower age increases continuously as flowers progress through the supply chain due to both transportation time and storage duration at production farms, distribution centers, and flower shops.

The concepts of freshness level and flower age differ fundamentally in the context of the mathematical model. Freshness level is a predefined label assigned to flowers at the production stage, reflecting their initial quality and suitability for market categories. This label remains constant throughout the supply chain journey, irrespective of the time elapsed or conditions during transportation and storage. In contrast, flower age is a continuous variable that measures the time elapsed since the flowers were harvested. Flower age increases as flowers move through the supply chain, influenced by factors such as transportation time, storage duration, and handling delays.

The assumption that the age of flowers at the distributor (A_j^f) is the same as the age of flowers at the flower shop (A_k^f) is valid due to the short delivery distance and the use of equipped vans. With deliveries typically occurring within a 5-mile radius, the transit time is minimal, ensuring that the flowers' age does not significantly increase during this stage. Additionally, the vans are equipped with temperature control systems, maintaining optimal conditions and preventing quality degradation during transportation. This assumption simplifies the model while accurately reflecting the negligible impact of this short transit on the flowers' freshness, allowing the focus to remain on earlier stages of the supply chain where aging and quality loss are more pronounced.

Γ represents the blockchain usage unit cost in the model. This cost reflects the expenses associated with implementing and maintaining blockchain technology across the supply chain. It includes the operational costs of storing, processing, and accessing data on the blockchain, such as tracking product conditions, verifying transactions, and ensuring transparency between supply chain partners. Table below shows the calculation of parameters which are used in the model (Table 1):

Table 1. Parameter calculations

Parameter	***Calculation***	***Definition***
IC_N	EN$* GW_N\ EM_N$	N2O emission impact cost (£)
IC_c	EC$* GW_C\ * EM_C$	CH4 impact cost (£)
WC_i	$CW_i * UC_i$	Total cost of water which is used for cultivation of one flower stem
FCE_l	$\frac{CF^l}{Fe_l}$	Fuel Cost Efficiency (Fuel consumption per distance)
EI_l	$\frac{EF}{Fe_l}$	CO2 Emission Intensity (Emission per distance)

The model formulation is as following:

Sets and parameters:

I: set of production farm sites ($i \in$ I)
J : set of wholesale (distribution) sites *($j \in J$)*
K : set of flower shops ($k \in K$).
L: set of vehicle types *($l \in L$)*.
F: set of freshness levels ($f \in$ F).

TL: set of available transportation links of i and j to ($TL \in I, J$) .

Parameters and functions:
Γ: blockchain usage unit cost.
c_i : per unit production farm cost at site i; $i \in I$.
FC_i : fixed cost of plant utilization i; $i \in I$.
TC_{ij}^l : per unit transportation cost between farm i and flower distribution j using vehicle type l; $(i,j) \in TL, l \in L$. (£)
TC_{jk}^l : per unit transportation cost between farm i and flower distribution j using vehicle type l; $j \in J$, $k \in K$, $l \in L$. (£)

t_{ij}^l : transportation time between production farm i and flower distribution j using vehicle type l, it also includes the processing and storage time. $(i,j) \in TL, l \in L$. (hour)

$t\bar{max}_{ij}$: maximum transportation time between production farm i and flower distribution j (i.e. $\max_l\{t_{ij}^l\})$; $(i,j) \in Tl$. (hour)
$\bar{A}^f$: maximum allowable flower age in flower farm for freshness level f; $f \in F$.
$\underline{A}_i$: age of flower before shipping at farm i (storage and processing time before shipping at farm) i , $i \in I$.

A^{max} : maximum allowable flower age in flower distribution j

A^{min} : minimum allowable flower age in flower distribution j

D_k^f: demand at flower shop k for flowers of freshness level f.

lcb_j / lc_j : one flower stem loss cost at flower distribution j when BCT has been / hasn't adopted ($lcb_j < lc_j$) (£)

$lcbp_i$ /lcp_i : one flower stem loss cost at production farm i when BCT has been / hasn't adopted ($lcbp_j < lcp_j$)

$lcbt_{ij}^{l}$ /lct_{ij}^{l}: one flower stem loss cost at transportation from i to j when BCT has been / hasn't adopted ($lcbt_{ij}^{l} < lct_{ij}^{l}$)

Cr^{l}: electricity used for refrigeration in transportation per hour for flower with using vehicle type l (kw/h)

Fe_{l}: fuel efficiency in transportation vehicle type l (km/litre)

CF^{l}: cost per unit of Fuel in transportation vehicle type l (£/lit)

dis_{ij} : distance between production farm i and flower distribution j. (km)

$capi^{l}$: capacity of lorry in transportation vehicle type l which moves from production farm i and flower distribution j

$capj^{l}$: capacity of van in transportation vehicle type l which moves from flower distribution j to flower shop k with

qf_{i}: quantity of fertilizer used in farm i per number of flower stems (kg)

EN: emitted N2O per kg of fertilizer (kg N2O/ kg fertilizer)

GW_{N}: global warming potential of N2O (CO2 equivalent per unit of N2O)

EC: emitted CH4 per kg of waste decomposition (kg CH4/ kg decomposition)

GW_{C} : global warming potential of CH4 (CO2 equivalent per unit of CH4)

EF: emitted CO2 per litre of fuel

LP: flowers loss percentage in transportation between facilities

CW_{i}: litre of water consumption for one flower stem in production farm i

UC_{i} : water usage cost per litre of water in production farm i (£)

EM_{C} : emission cost of Methan (CH4) per kg of usage (£/kg CO2 equivalent)

EM_{N} : emission cost of N2O per kg of usage (£/kg CO2 equivalent)

EM_{C02}: emission cost of CO2 per kg of usage (£/kg CO2 equivalent)

M_{K}^{f}: marketing expenditure of flower shop k for products with freshness level of f

a: constant intercept (base price) if demand, marketing, and quality are zero.

b: coefficient that represents how sensitive price is to demand changes (demand elasticity).

c: coefficient that represents how sensitive price is to marketing expenditures.

d: coefficient that represents how sensitive price is to flower age.

Decision variables:

x_{ij}^{lf}: quantity of products with freshness level f shipped between production farm i and flower distribution j using transportation vehicle type l; $(i,j) \in TL, l \in L, f \in F$.

x_{jk}^{lf}: quantity of products with freshness level f shipped between flower distribution j and flower shop k using transportation vehicle type l; $(j,k) \in TL, l \in L, f \in F$

P_k^f: sold price in flower shop k for product of freshness level f; $f \in F$.

q_i: quantity produced at production farm i; $i \in I$.

A_j^f: age of products of freshness level f at flower distribution j; $j \in TL, f \in F$.

y_{ij}^{lf}: $\begin{cases} 1 \text{ if transportation vehicle type } l \text{ is used to transport products of freshness level } f \text{ on link } (i,j);\ (i,j) \in TL, l \in L, f \in F \\ 0 \text{ otherwise.} \end{cases}$

r_{ij}^{l}: $\begin{cases} 1 \text{ if the travel time information of link } (i,j) \text{ using transportation vehicle type } l \text{ is stored on the blockchain;} \\ (i,j) \in TL, l \in L \\ 0 \text{ otherwise.} \end{cases}$

B_i: $\begin{cases} 1 \text{ if the flower farm } i \text{ information is stored on the blockchain;} \\ i \in I \\ 0 \text{ otherwise.} \end{cases}$

wh_j: $\begin{cases} 1 \text{ if flower disturbution } j \text{ information of is stored on the blockchain;} \\ j \in J \\ 0 \text{ otherwise.} \end{cases}$

z_i: $\begin{cases} 1 & \text{if flower farm } i \text{ is used; } i \in I \\ 0 & \text{otherwise.} \end{cases}$

$dist_j$: $\begin{cases} 1 & \text{if flower distribution } j \text{ is used; } j \in J \\ 0 & \text{otherwise.} \end{cases}$

$MAX\ Z = \sum_{k \in K} \sum_{f \in F} D_k^f P_k^f - \sum_{i \in I} c_i q_i - \sum_{(i,j) \in TL} \sum_{l \in L} \sum_{f \in F} TC_{ij}^l \frac{x_{ij}^{lf}}{capi^{lf}} - \sum_{(j,k) \in TL} \sum_{l \in L} \sum_{f \in F} TC_{jk}^l \frac{x_{jk}^{lf}}{capj^{lf}} - \sum_{i \in I} FC_i z_i - \sum_{(i,j) \in TL} \sum_{l \in L} \sum_{f \in F} \Gamma r_{ij}^l x_{ij}^{lf} - \sum_i \Gamma B_i q_i - \sum_{(i,j) \in TL} \sum_{l \in L} \sum_{f \in F} \Gamma wh_j x_{ij}^{lf} - \sum_f \sum_j \sum_i \sum_l Cr^l t_{ij}^l \frac{x_{ij}^{lf}}{capi^l} - \sum_{(i,j) \in TL} \sum_{l \in L} FCE_l * dis_{ij} * \frac{x_{ij}^{lf}}{capi^l} - \sum_{(i,j) \in TL} \sum_{l \in L} EI_l * dis_{ij} * \frac{x_{ij}^{lf}}{capi^l} * EM_{C02} - \sum_i qf_i * q_i * IC_N - [\sum_i \sum_j \sum_l \sum_f (x_{ij}^{lf}) - \sum_k (D_k^f)]$ $IC_c - [q_i - \sum_i \sum_j \sum_l \sum_f (x_{ij}^{lf})] * IC_c - LP * \sum_i \sum_j \sum_l \sum_f (x_{ij}^{lf})\ IC_c - [wh_j * lcb_j (\sum_i \sum_j \sum_l \sum_f (x_{ij}^{lf}) - \sum_k (D_k^f)) + (1\text{-}wh_j) * lc_j (\sum_i \sum_j \sum_l \sum_f (x_{ij}^{lf}) - \sum_K (D_K^f)) + B_i * lcbp_i * (q_i - \sum_f \sum_j \sum_l (x_{ij}^{lf})) + (1\text{-}B_i)\, lcp_i * (q_i - \sum_f \sum_j \sum_l (x_{ij}^{lf}))) +$ $r_{ij}^l * lcbt_{ij}^l * LP * \sum_i \sum_j \sum_l \sum_f (x_{ij}^{lf}) + (1\text{-}r_{ij}^l) * lct_{ij}^l * LP * \sum_i \sum_j \sum_l \sum_f (x_{ij}^{lf})] - \sum_i q_i * WC_i$	(2)
S.T.	(3)

$\sum_{j\in TL} \sum_{l\in L} \sum_{f\in F} x_{ij}^{lf} \leq q_i ; \quad \forall i \in I$	
$\sum_{i\in I} \sum_{l\in L} \sum_{f\in F} x_{ij}^{lf} = \sum_{k\in K} \sum_{l\in L} \sum_{f\in F} x_{jk}^{lf} \quad \forall j \in J$	(4)
$\sum_{(j,k)\in TL} \sum_{l\in L} x_{jk}^{lf} \geq D_k^f \quad \forall k \in K, \forall f \in F;$	(5)
$q_i \leq Mz_i \; \forall i \in I;$	(6)
$\sum_{i\in TL} \sum_{l\in L} \sum_{f\in F} x_{ij}^{lf} \leq Mz_i \quad \forall i \in I;$	(7)
$A_j^f \geq A_i^f + t_{ij}^l r_{ij}^l + tmax_{ij}(1 - r_{ij}^l) - M(1 - y_{ij}^{lf}) \quad \forall (i,j) \in TL, l \in L, f \in F;$	(8)
$A_i^f \leq \bar{A}^f \; \forall i \in I, f \in F;$	(9)
$A_i^f \geq \underline{A}_i \; \forall i \in I, f \in F;$	(10)
$x_{ij}^{lf} \leq My_{ij}^{lf} \; \forall (i,j) \in TL, l \in L, f \in F$	(11)
$r_{ij}^l \leq \sum_{f\in F} y_{ij}^{lf} \; \forall (i,j) \in TL, l \in L;$	(12)
$B_i \leq z_i \quad \forall i \in I$	(13)
$wh_j \leq dist_j \quad \forall j \in J$	(14)
$y_{ij}^{lf} \leq Mz_i \quad \forall (i,j) \in TL, l \in L, f \in F$	(15)
$y_{ij}^{lf} \leq dist_j \quad \forall (i,j) \in TL, l \in L, f \in F$	(16)
$P_k^f = \alpha - dA_k^f \quad \forall k \in K, \forall f \in F;$	(17)
$A_j^f \leq A^{max} \; \forall i \in I, f \in F;$	(18)
$A_j^f \geq A^{min} \; \forall i \in I, f \in F;$	(19)
$r_{ij}^l, y_{ij}^{lf}, z_j, B_i, dist_j, Wh_j \in \{0,1\} \; \forall (i,j) \in TL, l \in L, f \in F;$ $q_i, p_j^f, x_{ij}^{lf}, A_j^f, x_{jk}^{lf} \geq 0 \; \forall (i,j) \in TL, l \in L, f \in F.$	(20)

The equation 2 represents the objective function of the model, aiming to optimize the overall cost-effectiveness of flower production, distribution, and sales. This objective function includes minimizing costs associated with emissions (CO_2, N_2O, and CH_4), generated waste, water usage, and energy, as well as transportation and production expenses. Additionally, it may consider maximizing profits by managing the freshness and quality of products, reducing loss costs, and enhancing marketing expenditures to boost demand sensitivity. In the objective function we have modelled three goals we were aiming for in LCA; reducing the environmental impact (GHG emissions) in the life cycle of flowers as well as the waste generation in the cycle and finally the cost effectiveness of the activities in the cycle.

Constraint 3, regulates the total quantity of products shipped from each production farm i, ensuring it does not exceed the production farm capacity q_i. This keeps production output aligned with each location's resource availability and capabilities. Constraint 4 states that the total quantity of products arriving at each flower distribution site *j* from all production farms must match the total quantity sent from *j* to flower shops. This flow balance maintains consistency in inventory movement throughout the supply chain. Constraint 5, satisfies demand fulfilment requirements, ensuring that the total quantity of products with freshness level *f* shipped to each flower shop k meets or exceeds the demand D_k^f. This secures customer demand satisfaction for each freshness level at every shop. Constraint 6, links the production capacity q_i to the binary variable z_j, which indicates whether a site is active. When active, a site can produce up to a certain limit M; otherwise, it produces nothing. Constraint 7, satisfies the requirement of production farm to open if the shipment needs to come out of the farm. Constraint 8 regulates the age of products at site *j* after transportation, factoring in travel time from production farm *i*, whether refrigerated or not. This helps preserve product freshness based on transport conditions. Constraint 9 ensures that the product age at production farm i does not exceed the maximum allowable age for freshness level *f*, limiting how long products can be stored before distribution.

Constraint 10 enforces a minimum freshness level by requiring that products at production farm *i* meet a minimum age requirement, which may relate to a ripening or curing period before they are distributed. Constraint 11 controls the shipment quantity using the binary variable y_{ij}^{lf}, which indicates whether transportation of products is taking place. This constraint prevents shipments from being scheduled if y_{ij}^{lf}=0. Constraint 12, ensures that block chain implementation on transportation is only active when products of freshness level f are actually being transported. Constraint 13, guarantees that if only block chain is implemented in the production farm if the farm is open and operational. Constraint 14, regulates the storage feasibility for dist *j* to have block chain getting implemented if and only the flower distribution is open. Constraint 15, ensures that shipments from an production farm *i* occur only if the site is active. Constraint 16, enforces that shipments to distribution site *j* are feasible only if the flower distribution *j* is open to accept the shipment. Constraint 17, defines the pricing function, where the selling price for product freshness level *f* at flower shop *k* depends on demand, marketing, and product age. This aligns price with product quality and marketing efforts. Constraint 19, and Constraint 20, defined the maximum and minimum allowable product age threshold for flowers once they arrive at the flower distribution. Constraint 18 defines decision variables' types.

3. Result, discussion and sensitivity analysis

This section provides a comprehensive numerical example to illustrate the application of the developed model in optimizing the cut-flower supply chain. The example encompasses the input data, model formulation, and results obtained, offering insights into how blockchain technology (BCT) enhances supply chain efficiency. The input data for numerical example has been presented in Appendix. The model is coded in Python environment (using Jupiter Lab) and Gurabi has been used as the solver for integer programming. This numerical example illustrates how the developed model optimizes a complex cut flower supply chain by balancing production quantities, transportation flows, and technology adoption decisions. The integration of blockchain technology enhances traceability and accountability while minimizing costs associated with waste and inefficiencies. Upon solving the optimization model, an optimal objective value of 78,033.37 was achieved. This value signifies that the model effectively minimizes costs associated with transportation, production, and distribution within the cut flower supply chain. The gap between the best solution found to be 0.0000%, indicating that the solution is precisely optimal. The model produced balanced production quantities across all sites, with each production site generating 450 units. This uniform approach suggests that the model has successfully optimized resource allocation based on demand patterns and cost considerations. The transportation flows revealed significant movement from production farm i1 to wholesale site j2, with 9,550 units transported using mode l1 at freshness level f1. This indicates a high demand or lower transportation costs associated with this route.

In terms of blockchain adoption, all production farms implemented BCT, enhancing traceability throughout the supply chain. However, there was no adoption of blockchain technology in transportation or flower wholesale operations. This selective adoption reflects a strategic decision where the benefits of BCT in production outweigh its costs in other areas.

The model also demonstrated effective management of product freshness throughout the supply chain. Freshness constraints were met at all stages, ensuring that flowers maintained acceptable quality levels during transit and storage. Furthermore, all production farms and distribution sites were utilized optimally based on demand forecasts.

The impact of blockchain technology on cost management was significant. By providing real-time visibility into product conditions and facilitating swift issue resolution during transit—such as temperature fluctuations or mishandling—the model effectively minimized waste associated with spoilage or damage. Moreover, enhanced decision-making capabilities allowed for better inventory management and demand forecasting, preventing overproduction and excess stock.

The collaborative nature of blockchain technology fosters accountability among supply chain participants. By sharing data transparently, stakeholders are held responsible for maintaining quality standards throughout the supply chain process. This improved coordination helps align supply with demand more effectively, further reducing waste.

This analysis examines the impact of varying key parameters on the objective value of our supply chain optimization model. We conducted sensitivity analysis on five main parameters: Blockchain Cost, Transportation Costs, Freshness Penalty Costs, Emission Costs and Transportation Costs. We varied each parameter by -20%, -10%, 0% (base case), +10%, and +20%. The objective value was recalculated for each variation to observe the model's sensitivity to these changes.

Sensitivity analysis on Emission Costs (CO2, N2O, CH4)

In this section we investigate how variations in the costs associated with greenhouse gas emissions impact the model's objective value. Emission costs are tied to the environmental footprint of the supply chain, covering CO_2, N_2O, and CH_4 emissions generated through production, transportation, and distribution activities. By adjusting emission costs by -20%, -10%, 0% (base case), +10%, and +20%, this analysis assesses the model's responsiveness to changes in environmental costs, which reflects the financial implications of sustainability efforts within the supply chain. This sensitivity analysis is particularly valuable for evaluating how emission-related expenses affect the cost structure and identifying whether emission costs are a significant factor in the optimization strategy. The Table 2 below summarizes the changes in objective value across various levels of emission costs.

Table 2. impact of changes of emission costs on Obj value

Variation (%)	Objective Value
-20%	78,036.04
-10%	78,034.71
0% (Base)	78,033.37
+10%	78,032.03
+20%	78,030.69

The model demonstrates low sensitivity to changes in emission costs, confirming that environmental cost variations have only a minimal impact on the overall optimization outcomes. This suggests that the financial weight of emission costs within the supply chain is relatively small compared to more influential cost drivers like transportation, freshness penalties, and blockchain costs. As a result, fluctuations in emissions-related expenses do not significantly alter the objective value, making the supply chain model resilient to environmental cost changes.

Conversely, a 10% decrease in emission costs slightly improves the objective value to 78,034.71, and a 20% reduction raises it further to 78,036.04, confirming that lower emission costs provide only marginal financial benefits. This suggests that reducing emissions, while beneficial from a sustainability perspective, does not lead to significant cost savings within the model.

The findings highlight that emission costs play a minor role in supply chain decision-making compared to transportation, freshness penalties, and blockchain costs. This low sensitivity indicates that while sustainability remains important, financial incentives related to emission reductions are not a dominant factor in optimizing the supply chain. Companies may therefore focus on strategic sustainability initiatives for regulatory compliance and corporate responsibility without expecting major cost impacts from emission fluctuations.

Sensitivity analysis on Blockchain adoption

Figure 1 below provides a visual breakdown of the relative costs associated with implementing blockchain technology at different points in the supply chain, such as production, transportation, and wholesale stages. Each segment of the pie chart represents the share of blockchain costs incurred at a specific stage, allowing stakeholders to see where the highest expenses are concentrated. For example, if production shows a larger segment, it indicates that the majority of blockchain-related costs are tied to tracking and verifying processes at production sites, where real-time monitoring and traceability can prevent waste and improve quality assurance. Conversely, smaller segments for stages like transportation or wholesale suggest that blockchain might be less critical or cost-effective in these areas, as the benefits of real-time traceability may not outweigh the expenses. This visualization helps illustrate the financial considerations of selective blockchain adoption, allowing organizations to strategically allocate blockchain investments to stages where the value added justifies the associated costs, thereby supporting a more efficient and targeted approach to blockchain implementation.

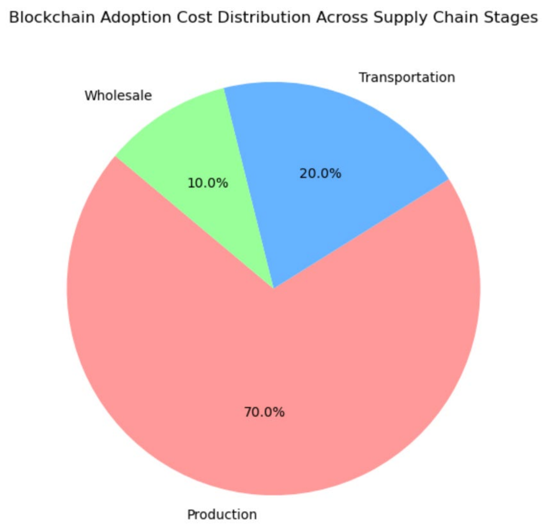

Figure 1. BCT adoption cost distribution

The heatmap in Figure 2 shows the costs across different routes, helping to identify cost-efficient or expensive routes. This is especially helpful when we are dealing with the transportation matrix that is complex and covers multiple nodes. each row represents a transportation route (e.g., from production site i1 to wholesale site j1), while each column corresponds to a transportation mode (e.g., Mode l1 and Mode l2). The cell values in the heatmap reflect the transportation costs associated with each route and mode, with the colour intensity indicating the cost magnitude. Lighter colours represent lower costs, while darker colours indicate higher costs. This visual differentiation allows for easy identification of high-cost routes, which may benefit from route optimization, alternative modes, or scheduling adjustments to control expenses.

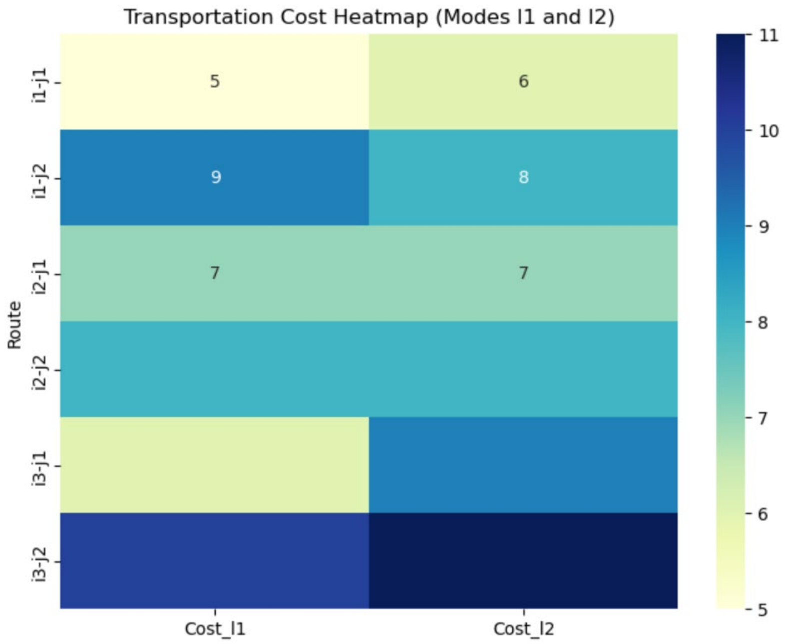

Figure 2. Transportation cost heat map

The integration of Blockchain Technology (BCT) into the cut-flower supply chain significantly improves both operational efficiency and sustainability. By providing real-time transparency and traceability, BCT enables better coordination among producers, distributors, and retailers, ensuring that flowers maintain optimal freshness from farm to shop. This reduces waste, lowers spoilage costs, and improves demand forecasting, helping businesses align production and inventory with actual market needs. The mathematical model presented in the study shows that BCT's selective adoption—particularly at production sites—maximizes value by enhancing accountability and product quality while keeping implementation costs minimal. Additionally, the ability to adjust prices dynamically based on freshness, supported by BCT data, allows retailers to improve profitability and better serve customer expectations.

On the environmental side, BCT plays a crucial role in reducing the carbon footprint of the supply chain. By minimizing waste and optimizing transport routes, BCT helps lower greenhouse gas emissions, including CO_2, CH_4, and N_2O, as captured in the life cycle assessment (LCA). It also promotes more efficient use of critical resources such as water and energy, particularly in refrigerated transport, and reduces the volume of floral waste that ends up in landfills. Sensitivity analyses in the study show that emission cost variations have only a minor impact on total supply chain costs, suggesting that companies can pursue sustainability goals without sacrificing economic performance. Overall, BCT offers a powerful tool to achieve both economic and environmental improvements, making it a valuable enabler of green, resilient supply chains in the floriculture sector.

4. Conclusion and managerial insights

This study presents a novel and comprehensive framework for optimizing the cut-flower supply chain by integrating Life Cycle Assessment (LCA) and Blockchain Technology (BCT). The proposed model effectively addresses critical sustainability challenges, including greenhouse gas emissions, waste generation, and cost inefficiencies, while ensuring product freshness and quality. By strategically incorporating BCT at key supply chain stages—primarily production—the model enhances traceability, transparency, and accountability. Numerical simulations demonstrate that blockchain adoption, though selective, significantly reduces waste and improves coordination, without incurring prohibitive costs. Sensitivity analyses further confirm the model's robustness, showing that while transportation costs have a moderate impact, emission and blockchain implementation costs have minimal effect on overall optimization outcomes. This work offers practical managerial insights for stakeholders aiming to balance environmental sustainability with operational efficiency, positioning blockchain as a viable enabler for the future of green supply chains in floriculture.

The model exhibits moderate sensitivity to fluctuations in transportation costs, reinforcing the importance of this factor in supply chain optimization. While transportation costs significantly influence overall efficiency, their impact is not overwhelmingly dominant. This suggests that while optimizing transportation strategies—such as route selection, freight negotiation, and logistics technology investment—can enhance cost-effectiveness, other factors must also be considered for a balanced optimization approach.

Blockchain implementation costs show minimal influence on the model's overall performance, indicating that the financial burden of adoption does not substantially disrupt optimization outcomes. This implies that blockchain's benefits—such as enhanced traceability, data security, and fraud prevention—can be leveraged without major cost concerns. Thus, companies looking to improve supply chain transparency and reliability may find blockchain integration a valuable long-term investment.

The model achieves balanced production across farms, ensuring consistent output to meet demand. However, transportation flows exhibit asymmetry, driven by regional demand variations across distribution centres. This suggests that while production is uniformly allocated, an adaptive distribution strategy is needed to optimize logistics in response to shifting demand patterns.

The model successfully integrates production, transportation, and freshness considerations while selectively adopting blockchain to enhance traceability without unnecessary cost burdens. The sensitivity analysis underscores that while transportation costs are important, other factors—such as production efficiency, demand-driven logistics, and strategic blockchain implementation—play equally vital roles in optimizing supply chain operations. The findings emphasize the need for a multi-dimensional approach to supply chain management that balances cost efficiency, quality assurance, and technological innovation.

References

Acuna-Agost, R., Thomas, E., & Lhéritier, A., Price elasticity estimation for deep learning-based choice models: an application to air itinerary choices. In *Artificial Intelligence and Machine Learning in the Travel Industry: Simplifying Complex Decision Making* (pp. 3-16): 2023, Springer.

Babich, V., & Hilary, G., OM Forum—Distributed ledgers and operations: What operations management researchers should know about blockchain technology. *Manufacturing & Service Operations Management, 22*(2), 223-240, 2020.

Breiner, S. J., *Perceptions and attitudes of cow-calf producers toward emerging technologies and policy issues in the beef cattle industry.* Kansas State University, 2007.

Chauhan, A., Chauhan, M., Sethi, M., Bodhe, A., Tomar, A., Shikha, & Singh, N., Application of Flower Wastes to Produce Valuable Products. *Valorization of Biomass Wastes for Environmental Sustainability: Green Practices for the Rural Circular Economy*, 251-268, 2024.

Dey, S., Veerendra, G. T. N., Padavala, S. S. A. B., & Manoj, A. V. P. , Evaluate the use of flower waste biosorbents for treatment of contaminated water. *Water-Energy Nexus, 6*, 187-230, 2023.

Hasna, P., Rafeekher, M., Priyakumari, I., & Reshmi, C., Flower Forcing: A Review. *International Journal of Plant & Soil Science, 36*(6), 592-600, 2024.

Kulak, M., Graves, A., & Chatterton, J., Reducing greenhouse gas emissions with urban agriculture: A Life Cycle Assessment perspective. *Landscape and urban planning, 111*, 68-78, 2013.

Lan, Y.-C., Tam, V. W., Xing, W., Datt, R., & Chan, Z., Life cycle environmental impacts of cut flowers: A review. *Journal of Cleaner Production*, 133415, 2022.

Reddy, C. O., & Sirisha, V. S., Management of Floral Waste, as Well as Various Techniques and Approaches for Converting the Floral Waste into Value-Added Products. In *From Waste to Wealth* (pp. 825-838), 2024: Springer.

Reisch, L., Eberle, U., & Lorek, S., Sustainable food consumption: an overview of contemporary issues and policies. *Sustainability: Science, Practice and Policy, 9*(2), 7-25, 2013.

Wamba, S. F., Akter, S., Edwards, A., Chopin, G., & Gnanzou, D., How 'big data'can make big impact: Findings from a systematic review and a longitudinal case study. *International journal of production economics, 165*, 234-246, 2015.

Wang, G., Gunasekaran, A., Ngai, E. W., & Papadopoulos, T., Big data analytics in logistics and supply chain management: Certain investigations for research and applications. *International journal of production economics, 176*, 98-110, 2016.

Xu, S., Zhao, X., & Liu, Z., *The impact of blockchain technology on the cost of food traceability supply chain.* Paper presented at the IOP Conference Series: Earth and Environmental Science, 2020.

Biographies

Zahra Mohammadnazari is a researcher specializing in operations management, business analytics, and productivity policy. She is currently completing her PhD in Business Management and Social Sciences at Coventry University, with a focus on operations research, data science, and sustainability. Zahra has extensive experience leading international research projects, including EU-funded initiatives, and has published widely in top-tier academic journals. Her work bridges the gap between research and policy, delivering actionable insights for improving productivity and sustainable development. She is also a Fellow of the Higher Education Academy and an active member of professional bodies.

Mahdi Bashiri is an associate professor at the Research Centre for Business in Society at Coventry University. He has over 20 years of academic experience with a particular interest in operations and supply chain management, operations research, transportation planning, and Heuristic and Matheuristic algorithms. Also, he has participated in industrial and business projects at different levels. He has been involved in two UKRI-funded projects and two British Academy-funded awards. He has supervised more than 10 PhD students. He is an active reviewer for reputable academic journals.

David Bek is Professor of Creative Economies and Ecological Sustainability at the Research Centre for Creative Economies (CCE) at Coventry University (UK). David has more than 20 years' experience of undertaking research into sustainability within horticultural supply chains, especially cut-flowers. He is co-lead of the Sustainable Flowers Research Project which has been running since 2016. David's work in the cut-flower sector has taken him to Holland, South Africa, Kenya, Mexico, Spain and the USA. His research covers a range of aspects of the cut-flower industry and wider horticultural sector including: global production and trade patterns; consumer attitudes and trends; economic and social impacts of flower production and trade; certifications; and environmental sustainability. David is an economic geographer whose work draws heavily upon Global Production Networks and Global Value Chain theory.

Appendix
Input data for numerical example

The input data utilized in this numerical example is presented in several tables. Table 3 outlines the production sites, highlighting critical parameters such as production costs, fixed costs associated with plant utilization, and loss costs related to both blockchain adoption and non-adoption. For instance, production farm i1 has a production cost of 10 per unit and a fixed cost of 100, while loss costs vary depending on whether BCT is implemented. This structured approach allows stakeholders to assess the economic implications of adopting blockchain technology at different stages of the supply chain.

Table 3. Production farms and Costs

Farm	Production Cost c_i	Fixed Cost Fc_i	BCT Loss Cost $LCBP_i$	Non-BCT Loss Cost LCP_i
i1	10	100	0.5	0.7
i2	12	120	0.2	0.9
i3	15	220	0.3	1.1

The forth table focuses on flower wholesale sites, detailing their respective loss costs when BCT is adopted or not. This information is crucial as it illustrates how blockchain can mitigate losses during distribution. This table presents transportation costs and times associated with various transportation modes between production and wholesale sites. It emphasizes the importance of selecting optimal transportation routes to minimize costs while ensuring timely delivery of fresh products. Additionally, customer demand is captured in a separate table that specifies demand levels for different freshness categories. This data is vital for aligning production quantities with market needs, ultimately reducing waste due to unsold inventory.

Table 4. Wholesale Sites and Costs

Site	BCT Loss Cost LCB_i	Non-BCT Loss Cost LC_i
j1	0.4	0.8
j2	0.3	1.0

Table 5. Transportation Costs and Times

Link	Mode	Cost	Time
i1-j1	l1	5	1
i1-j1	l2	6	1.5
i2-j2	l1	7	2
i2-j2	l2	8	2.5
i3-j2	l1	9	3
i3-j2	l2	10	3.5

Table 6. Customer Demand

Zone	Freshness Level	Demand
k1	f1	100
k1	f2	150
k2	f1	200
k2	f2	250