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Simulation-driven comprehensive performance analysis of cold chain logistics for export flowers in emerging economies: Insights from the Ethiopian floriculture industry

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Background: Growing international trade in floricultural products has increased the importance of cold chain logistics (CCL) for preserving quality, shelf life and export competitiveness. However, conventional evaluation approaches poorly capture the operational, economic and environmental complexities of floriculture cold chains.

Objectives: This study aims to develop an integrated framework for analysing export-flower CCL in an emerging economy, using the Ethiopian floriculture industry context.

Method: A multi-stage design that integrates a literature review, expert evaluation, the analytic hierarchy process (AHP) and discrete event simulation (DES) was adopted, structuring CCL evaluation into hierarchical dimensions, indicators and metrics within the DES model.

Results: Simulation results revealed substantial heterogeneity across growers. Daily throughput ranged from 201 to 4870 boxes and mean process times from 41.85 h to 44.84 h, while shelf-life consumed varied from 13.73 h to 22.55 h. Environmentally, the international flight stage accounted for the highest energy use (97.8%) and emission levels.

Conclusion: Disparities emerged in operational efficiency, responsiveness, quality, economic and environmental performance. Large-scale operations achieved higher throughput and lower cost per box, but not necessarily better environmental outcomes. Quality results, temperature degree-hours and shelf-life consumed varied with temperature management and process stability, underscoring the need for tailored interventions.

Contribution: The study integrates multi-criteria prioritisation with simulation-based system analysis in floriculture exports, offering evidence-based insights for growers, logistics providers, handling agents and policymakers seeking to improve effectiveness, minimise losses and enhance sustainability.

Keywords: cold chain logistics; comprehensive performance analysis; analytic hierarchy process; discrete event simulation; floriculture; Ethiopia.

Introduction

Fresh agricultural products (FAPs) occupy a central position in the global economy, with a 30% growth in global demand since 2018, reaching a value of 1.17 trillion USD (ITC 2024). The expanding global trade in perishable goods has made efficient and reliable cold chain logistics (CCL) increasingly vital for meeting consumer demand and adhering to strict quality and safety regulations (Khan, Imran Khan & Haleem 2018). In addition, the increasing demand for high-quality and safe fresh produce has necessitated the development and optimisation of CCL systems (Liu & Zhou 2017). The floriculture industry, a significant component of FAPs, specialises in the cultivation, production, and marketing of ornamental plants and flowers (Hammond et al. 2023). The industry is characterised by high-value products and the need for careful handling to maintain product quality from farm to consumer. Cut flowers are particularly sensitive because their commercial value relies on timely delivery, visual quality, freshness, and shelf life at the

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destination (Verdonk et al. 2023). Consequently, the floriculture industry relies heavily on effective CCL to maintain product integrity from harvest to international market delivery (Karpun 2020; Van der Vorst, Bloemhof & De Keizer 2012). In export-oriented systems, this requirement becomes more critical because export flowers are exposed to multiple stages, transport modalities, storage operations, and time-sensitive decision points before reaching their destination (Bremer 2018).

A CCL can be understood as an integrated system of equipment, procedures, and processes that work together to maintain the temperature of temperature-sensitive products in a regulated environment throughout the journey (Bremer 2018; Joshi, Banwet & Shankar 2011). It plays a crucial role in maintaining the quality and extending the shelf life of perishable agricultural products (Zheng 2015). However, managing cold chains is inherently complex because they operate across multiple organisations. This complexity becomes more critical because exported flowers are exposed to multiple stages, each governed by its own set of standards (Bremer 2018; Fan et al. 2021). The involvement of multiple stakeholders, coupled with dependence on advanced infrastructure and technology, makes the cold chain vulnerable to disruptions (Jaelani et al. 2025). Furthermore, managing cold chains requires balancing competing goals, including quality preservation, cost efficiency, responsiveness, and environmental sustainability (Fan et al. 2021). These unique characteristics of CCL present distinct challenges that necessitate specialised evaluation methods. However, conventional logistics evaluation methods do not sufficiently capture the complexities and critical metrics specific to cold chain operations (Liu, Zhao & Zhang 2018).

Consequently, measuring cold chain performance requires further investigation, given the distinctive characteristics of cold chains as compared to conventional supply chains. An effectively managed cold chain ensures that flowers reach consumers under optimal conditions, thereby enhancing customer satisfaction and the competitiveness of the floriculture industry in the global market (Macheka & Kockelkoren 2012). Thus, assessing the performance of CCL is essential for identifying areas for improvement, such as optimising transportation routes, improving packaging techniques, and implementing more robust monitoring systems (Joshi et al. 2011). A growing body of literature has examined cold chain performance in the food, fruit, and other perishable sectors. Studies have examined various aspects of CCL, including temperature control, packaging, storage, and transportation (Guaita-Pradas, Rodríguez-Mañay & Marques-Perez 2023; In et al. 2016; Van Meeteren, Schouten & Woltering 2012; Woltering & Paillart 2018). However, a recent systematic review of CCL on FAPs reported that the floriculture industry has received insufficient attention in the literature (Gugusa et al. 2026). Similarly, although simulation approaches have been applied to perishable supply chains, including fresh produce route optimisation (Jiayang, Linan & Dongyan 2018) and cold storage operations (Zhu et al. 2014), their application in comprehensive performance measurement in floriculture export logistics remains limited. These limitations reveal both sectoral gaps, reflected in the limited attention to floriculture cold chains, and methodological gaps, reflected in the limited use of simulation-based performance evaluation. Together, these studies constrain our understanding of how to tailor logistics strategies to the unique demands of the floriculture industry. A performance evaluation framework tailored to floriculture logistics and capable of incorporating stochastic operational conditions and multiple performance objectives is required.

Hence, this study addresses that need by developing and applying a simulation-driven comprehensive performance analysis framework for the export of CCL in the Ethiopian floriculture industry. Ethiopia provides an important setting because floriculture is a significant export activity that operates under infrastructural, coordination, and environmental constraints typical of emerging economies (Gobie 2019; Yeshiwas & Workie 2018). The framework integrates the identification, prioritisation, and operationalisation of performance parameters, informed by a literature review, expert evaluation, the Analytic Hierarchy Process (AHP), and a Discrete Event Simulation (DES) model parameterised with empirical data, to evaluate CCL across operational, economic, and sustainability dimensions.

The significance of this study is threefold, offering methodological, practical, and theoretical contributions to the CCL research in the floriculture sector. Firstly, it develops a hierarchical multi-criteria performance measurement framework designed for floriculture CCL. Secondly, the framework was operationalised using an empirically grounded DES model capable of capturing the stochastic process behaviour of the cut-flower export cold chain system. Thirdly, it provides empirical insights into inter-grower performance disparity and the trade-off among quality preservation, cost efficiency, and environmental impact. This study offers applicable insights to enhance efficiency, reduce product losses, and promote sustainability within the floriculture cold chain. It provides growers, exporters, logistics providers, and policymakers with evidence-based recommendations to enhance sector-wide competitiveness. Overall, this study contributes to CCL performance analysis and simulation modelling by integrating theoretical perspectives with practical solutions for challenges in the floriculture industry.

The remainder of this paper is organised as follows: Section 2 reviews the relevant literature and the study context. Section 3 presents the methodological framework and simulation modelling approach. Section 4 reports and discusses the main findings, while Section 5 concludes the study and outlines implications and future research directions.

Literature review

Overview of cold chain logistics and the floriculture industry

The floriculture industry involves the cultivation, processing, marketing, and international trade of flowers and ornamental plants (Anumala & Kumar 2021). As a high-value agricultural sector, it is characterised by high perishability, stringent quality requirements, and reliance on global distribution networks (Malakar et al. 2023). The sector has shown substantial growth driven by rising consumer demand, particularly in Europe, North America, and parts of Asia, where flowers are integral to cultural practices (Misra & Baskaran 2020). The global distribution and market share of floral products have evolved with significant trends in the primary export and import regions. The Netherlands, known for its advanced horticultural logistics capacity and export networks, is a prominent player in the global floriculture market (Rodríguez Mañay, Guaita-Pradas & Marques-Perez 2022). Other key contributors include Ecuador, Colombia, Kenya, and Ethiopia (Guaita-Pradas et al. 2023).

Cold chain logistics development has been central to the international expansion of the floriculture industry. Temperature-controlled storage, refrigerated transportation, and improved monitoring systems have enabled flowers to be transported over long distances while preserving their freshness and market value (Karpun 2020). These advances have facilitated the adoption of real-time monitoring and control systems that track temperature and humidity throughout the supply chain, ensuring that flowers remain under optimal conditions from farm to consumer (Van der Vorst et al. 2012). These technologies are essential for maintaining cold chain integrity and minimising spoilage risk (Chen & Lan 2016). In recent years, the focus has shifted towards sustainability and efficiency. The industry has introduced green cold chain practices to reduce the environmental impact of refrigeration and transportation, including the use of energy-efficient refrigeration units, eco-friendly packaging materials, and optimised logistics routes to minimise carbon emissions (Khan et al. 2020; Meneghetti & Monti 2015). These developments underscore the industry's ongoing efforts to improve flower quality and longevity while addressing environmental and economic challenges. Advances in technology and infrastructure have been instrumental in shaping the modern floriculture supply chain, enabling consumers to receive fresh, high-quality flowers regardless of geographical location (Fan et al. 2021; Saif & Elhedhli 2016).

Importance of cold chain logistics

Cold chain logistics play a fundamental role in ensuring that perishable goods, including fruits, vegetables, and other fresh produce, maintain their quality and safety from farm to final consumer. Through a series of temperature-controlled environments, CCL prevents spoilage and extends product shelf life (Fan et al. 2021). A primary benefit of effective CCL is the reduction of food waste, which is particularly significant given the global challenge of food security and the need to maximise food distribution efficiency (Du Plessis, Van Eeden & Goedhals-Gerber 2024; Liu et al. 2018). Moreover, the CCL is central to ensuring food safety by maintaining the required temperature threshold throughout storage, transport, and handling. Maintaining a consistent cold chain significantly reduces the risk of foodborne illnesses, thereby protecting public health and ensuring that consumers receive safe, high-quality products (Du Plessis, Van Eeden & Goedhals-Gerber 2022; Fan et al. 2021). The economic implications of CCL are also significant. For instance, the South African fruit industry, which exports large quantities of fresh fruit to international markets, benefits greatly from robust CCL systems (Du Plessis et al. 2022; Jiayang et al. 2018). Beyond economic benefits, CCL has environmental implications. Studies have shown that further research is needed to establish the relationship between cold chain duration, energy use, and emissions, underscoring the importance of sustainable practices (Du Plessis et al. 2024; Wu et al. 2019).

For the floriculture industry, CCL ensures that flowers are transported under optimal conditions to preserve their quality through a series of temperature-controlled environments from harvest to the final consumer. The effectiveness of this logistics chain directly affects the vase life of cut flowers, which is a critical quality parameter for consumers. For example, studies have shown that maintaining specific temperature and humidity levels can significantly extend the vase life of cut roses (In et al. 2016). Despite advancements in CCL, the floriculture industry faces several challenges. One of the primary issues is the variability in agricultural practices across different regions, which can affect the quality and consistency of the flowers produced (Wu et al. 2019). Moreover, the floriculture industry must navigate the complexities of international trade, including compliance with regulations and management of supply chain disruptions. The latter has become particularly evident as geopolitical tensions and global events, such as the coronavirus disease 2019 (COVID-19) pandemic, have caused significant supply chain disruptions, leading to delays, increased costs, and reduced flower availability in the market (Ksoll, Macchiavello & Morjaria 2023). To address these challenges, ongoing advancement in research and innovation is essential. The implementation of advanced operational strategies, such as real-time monitoring and data analytics, offers promising avenues for improving the efficiency and reliability of CCL systems (Fan et al. 2024).

Performance measurement in cold chain logistics

Cold chain logistics performance in agricultural cold supply chains encompasses a wide range of factors that contribute to the overall success and sustainability of the system. Conventional performance evaluation methods primarily assess operational efficiency using input–output ratios and are ill-suited for perishable products, as they treat product quality as an exogenous constraint on performance outcomes (Liu et al. 2018). These methods have additional limitations, including an overreliance on qualitative indicators and a lack of comprehensive evaluations. Research on CCL performance for FAPs has been extensive, focusing on various aspects, such as temperature control, quality maintenance, and sustainability (Han et al. 2021; Liu & Zhou 2017; Titlo & Sopadang 2019). Temperature abuse remains a critical issue in cold chain systems. It has been shown that precooled produce retains its shelf life more effectively than non-precooled produce (Conradie, Goedhals-Gerber & Van Dyk 2022). Determining the critical quality parameters at all stages of the CCL is another challenge. For example, in the case of table grapes, real-time temperature monitoring is essential for accurately evaluating quality (Xiao et al. 2016). This highlights the broader need for precise and continuous monitoring throughout the CCL to maintain the quality of perishable products.

However, evaluating the performance of a CCL is complicated by various factors, including shelf life restrictions, seasonality of production, and the need for refrigerated transportation and storage (Titlo & Sopadang 2019). The cold chain is inherently complex, requiring a balance among cost efficiency, quality, and sustainability, three objectives that often conflict because improving product and environmental quality frequently incurs additional costs (Fan et al. 2021). Accordingly, performance evaluation methods must consider complex operations, organisational capabilities, and external collaboration. Continuous monitoring systems, particularly during the transport and handling phases, significantly influence product quality and operational efficiency (Titlo & Sopadang 2019; Xiao et al. 2016). Comprehensive indicator systems encompassing financial performance, service quality, operational efficiency, and organisational capacity enable robust cold chain management (Defraeye et al. 2016; Shashi & Singh 2015; Turan & Ozturkoglu 2022). Comprehensive CCL performance measurement is widely recognised as important, but there is no consensus on what to measure or how to aggregate measures. Several studies focus on specific metrics such as energy consumption, carbon emissions, food waste, service quality, and cost, often treating them as separate performance dimensions rather than merging them into a single score (Kashav et al. 2018; Kumar, Tyagi & Sachdeva 2022; Xie et al. 2022). In agricultural cold chains, key performance indicators (KPIs) such as product waste cost, operating costs, on-time delivery, in-transit loss, and user satisfaction are treated as distinct measures (Kumar, Tyagi & Sachdeva 2023; Li & Qi 2016). In contrast, other studies explicitly construct composite evaluation systems, aggregated using methods such as entropy weighting, fuzzy evaluation, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), or catastrophe progression to yield an overall performance or sustainability score for cold chain enterprises or regions (Gunasekaran & Kobu 2007; Sun, Hu & Liu 2023; Yu & Zhang 2024).

The literature on CCL performance for Fresh Agricultural Products (FAPs) reveals several gaps relevant to the floriculture industry. A significant gap exists: No comprehensive performance measurement model tailored specifically for floriculture cold chains (Gugusa et al. 2026). Although existing studies have developed frameworks for evaluating cold chain performance in sectors such as agriculture, food products, and pharmaceuticals, these models do not fully capture the unique characteristics and requirements of the floriculture industry (Kumar et al. 2022; Rodríguez Mañay et al. 2022). Moreover, existing studies often overlook CCL’s environmental impact: The carbon footprint and energy consumption associated with refrigeration and transportation are critical factors in developing sustainable cold chain practices (Du Plessis et al. 2024; Liu et al. 2018). Furthermore, there is a gap in our understanding of the specific challenges faced by floriculture cold chains in different geographical regions and climates. Seasonality and variability in production, as well as diverse climatic conditions, can significantly affect cold chain performance. Studies addressing these regional and climatic differences are limited, and more localised research is needed to develop tailored solutions for different contexts (Asante et al. 2019; Titlo & Sopadang 2019). Together, these gaps highlight the need for a specialised floriculture CCL performance model that integrates environmental impacts, regional specificity, holistic evaluation, and standardised indicators.

Study context

Ethiopia has emerged as a major player in global floriculture, ranking second in Africa and fifth worldwide for flower exports. The sector has grown significantly since the early 2000s, driven by government investment policies, favourable highland agro-climatic conditions, and proximity to air-freight infrastructure at Addis Ababa Bole International Airport (Ethiopian Horticulture Producers Association [EHPEA] 2023). According to the National Bank of Ethiopia, floriculture remains a leading merchandise export sector: In 2023 to 2024, flower exports generated USD 469.9 million, accounting for 12.4% of total merchandise export earnings (NBE 2024). The export flower CCL system involves three main participant categories: Growers, refrigerated truck transport providers, and handling agents, each contributing to the processing and exporting of flowers to diverse global markets. The Ethiopian floriculture industry comprises diverse growers, including large international firms, small and medium enterprises (both local and foreign-owned), joint ventures, and development banks. The Ethiopian flower export CCL begins with growers harvesting flowers that have matured for cutting. Flowers then pass through essential procedures such as pre-cooling, sorting, cleaning, de-leafing, grading, bunching, and quality inspection to meet the export standards.

Flowers are packaged, boxed, and labelled for traceability and transportation. The packaged flowers are then stored at controlled temperatures in the grower’s facilities to maintain their quality until shipment. Refrigerated trucks then transport the flowers, ensuring temperature-controlled transportation from the farm gate to the airport handling facilities. Upon arrival at the airport, trucks await customs clearance, a stage that underscores the importance of regulatory coordination in minimising delays and preserving product quality. The handling agent, represented by the airport perishable cargo division, operates an advanced cold storage facility spanning 3700 m^2 and capable of accommodating cargo for up to four aircraft. After clearance, the flowers are sent to a receiving area for inspection of temperature records, quantities, and damage. The flowers are then unbatched, consolidated, palletised, and temporarily stored in cold storage facilities at the airport. Finally, the flowers are loaded onto aircraft and transported under controlled conditions to their destinations.

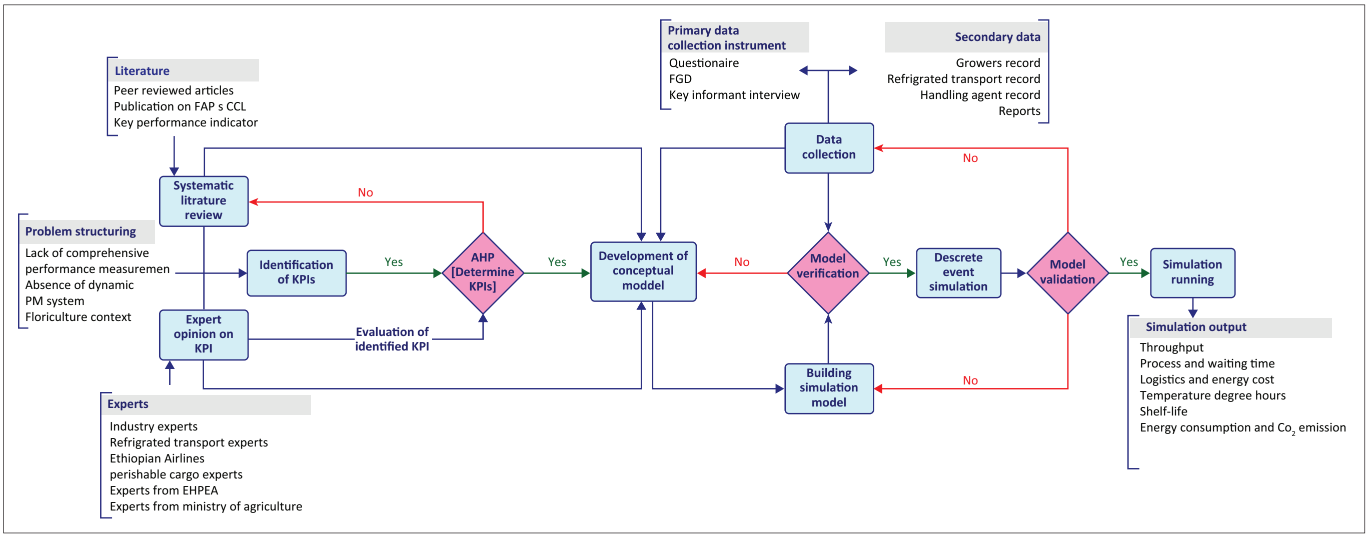
Research methods and design

Research design

This study adopts a multistage methodological framework integrating a literature review, multi-criteria decision-making, conceptual modelling, and simulation (Figure 1), selected to ensure methodological coherence between the development of the performance measurement framework and system analysis. The overall logic of the research design was as follows: Firstly, the relevant performance dimensions, indicators, and metrics for CCL in FAPs were identified from the literature. Secondly, an expert-based evaluation and prioritisation were undertaken to select the most appropriate performance parameters for evaluating CCL performance in floriculture using the AHP. The AHP was chosen because it has been extensively applied in supply chain and logistics decision problems, and a survey of 15 application papers by Vaidya & Kumar (2006) confirmed supply chain and logistics as among the most prominent application domains. Thirdly, the floriculture export CCL was represented using conceptual modelling. Flowchart and business process model and notation (BPMN) diagrams were used to visualise the flow of flowers, resources, and information across the system. The conceptual model defines the system boundaries, entities, activities, and decision points that serve as the structural basis for simulation modelling. Fourth, the conceptual model was translated into a DES model implemented in AnyLogic 8.9.4 (University Edition) (The AnyLogic Company, Oakbrook Terrace, IL, USA). Discrete Event Simulation was selected because it is well-suited to modelling dynamic, stochastic processes characterised by discrete events, resource constraints, and process variability. Finally, the simulation outputs were analysed using the AHP-informed performance structure.

Identification and selection of performance dimensions, indicators, and metrics

The first stage comprised a structured review of peer-reviewed literature on CCL performance for FAPs. This stage identified a broad pool of potential performance parameters relevant to the logistics of perishable products. This review supports the development of a hierarchical performance structure comprising dimensions, indicators, and metrics. To select and prioritise the potential performance parameters, expert-based evaluations and judgements were collected using evaluation criteria and pairwise comparisons. The study engaged a panel of 27 domain experts, comprising stakeholders directly involved in floriculture logistics, including farm managers, logistics professionals, representatives from the EHPEA, the Federal Democratic Republic of Ethiopia (FDRE) Ministry of Agriculture, Ethiopian Agriculture Authority, Refrigerated Truck transport service providers, academia, and handling agents for perishable cargo operations. Their assessment was used to select the relevant performance dimensions, indicators, and metrics for the flower export CCL, which assisted in developing a hierarchical performance measurement structure. Pairwise expert judgement was also used to compare the relative importance of the selected dimensions, indicators, and metrics within the hierarchy. These weights provide a conceptual basis for interpreting and analysing simulation outputs from a prioritised-performance perspective.



FAPs, fresh agricultural products; CCL, cold chain logistics; KPI, key performance indicators; AHP, the analytic hierarchy process; EHPEA, the Ethiopian Horticulture Producers Association; FGD, focus group discussion; PM, performance measurement.

FIGURE 1: Methodological framework of the study.

Conceptual modelling

Conceptual modelling was used to define the system boundaries, entities, process stages, decision points, and information flows. The conceptual model represents the end-to-end flow of flowers from harvesting to export and highlights the operational mechanisms that affect the system performance. The conceptual model was developed using the BPMN representation. The BPMN captured the sequential operational logic of the CCL, organised by actor lanes (Market, Grower or Exporter, and Handling Agent), showing material flow, information flow, and explicit coordination requirements. The conceptual model was validated through structured focus group discussions with seven participants from each major stakeholder group, following the procedure recommended by Robinson (2020). The participants reviewed the process representations, drawing on their operational experience, and confirmed the scope and structure of the model.

Data collection and parameterisation

Data collection followed the multi-stage design of the study. Initially, a structured review of 48 peer-reviewed studies was conducted to identify performance dimensions, indicators, and metrics relevant to CCL performance for FAPs. These parameters were subsequently evaluated and prioritised through expert judgments using a pairwise comparison questionnaire based on Saaty's AHP scale. The expert panel comprised professionals from flower-growing firms, refrigerated transport providers, handling agents, academia, the EHPEA, the FDRE Ministry of Agriculture, and the Ethiopian Agriculture Authority. Empirical data for conceptualisation and simulation parameterisation were collected through direct observation, semi-structured interviews, and historical operational records from flower growers, refrigerated transport providers, and handling agents for perishable cargo. These data enabled an accurate representation of the operational processes and system interactions. Data were collected from eight growers representing different operational scales within the Ethiopian floriculture export sector. The data points include shipment-level information on throughput, service times, transportation times, temperature, cost, and energy-related variables.

To represent the operational uncertainty and variability within the system, stochastic probability distributions were fitted to the key input variables using empirical observations. Beta distributions were used to model the handling-agent processing time and temperature variables because these variables exhibited bounded behaviour within the operational minimum and maximum limits. In addition, normal distributions were applied to relatively stable operational processes, such as flight time and cold storage temperature, because these variables fluctuate around constant mean values with limited variability. Triangular distributions estimated through expert judgment were used for harvesting and for selected service-time variables, where empirical observations were unavailable. This distribution is appropriate for representing uncertain processes using minimum, most likely, and maximum estimates. The daily order size was represented using a Poisson distribution to reflect the demand variability associated with seasonal and demand-driven export patterns. The input data and fitted distributions were integrated into the DES model using the AnyLogic database functionality to support a realistic system representation.

Discrete event simulation model development and validation

The conceptual model was translated into a DES model using AnyLogic 8.9.4 (University Edition). Discrete Event Simulation was selected because the floriculture cold chain is governed by discrete operational events occurring over time, including arrivals, service completions, loading activities, transport time, inspections, and storage transitions. The modelling approach also allows for the explicit representation of resource constraints, queue formation, process variability and time-dependent quality exposure. The simulation model was designed to reproduce the physical and decision logic of export CCL and to generate output data for each KPI included in the performance framework. The DES model was validated using both qualitative and quantitative approaches. The model's validity was qualitatively assessed through an industry expert review to verify the logic, structure, and realism of the DES. Historical process knowledge and observed operational patterns were used to assess the plausibility of the simulation representation. In addition, quantitative validation was conducted by comparing the simulation output with independently collected historical performance data. Three performance metrics were tested across all eight growers: Daily throughput (total boxes shipped to the international market), total shelf life consumed (hours), and total process time (hours). All tests accepted the null hypothesis, which states that the simulation output and historical records follow the same distribution, constituting statistical validation of the model across the performance dimensions. The simulation experiment was configured as a terminating simulation executed for 720 h, representing 30 days of consecutive cold chain operations. A pilot experiment with 10 replications was conducted to estimate the output variance and determine the required number of replications based on the confidence interval precision. Accordingly, 30 independent replications were conducted using random seeds to ensure statistical reliability.

Ethical considerations

This study did not involve human participants as research subjects. Data were collected from commercial operational records and expert consultations with participants willing to share their professional experiences. The research was registered with the Liverpool John Moores University, University Research Ethics Committee (UREC) under the Minimal Risk Registration Number 23/MME/23 and approved by the Research Governance Assessment. All participating professionals and organisations provided written informed consent to the use of their operational data in anonymised form. Confidentiality was maintained throughout the study by removing identifiers that could link operational data to specific organisations.

Results and discussion

Performance measurement framework for cold chain logistics of flower export

The performance measurement framework developed in this study (Figure 2) adopts a hierarchical multi-criteria structure, integrating insights from literature synthesis and expert-based evaluation to determine parameters relevant to CCL performance in the floriculture context. This structured approach reflects the systemic progression from the conceptual identification of performance parameters to quantitative prioritisation, ensuring both theoretical and empirical validity. The framework is organised into three hierarchical levels: performance dimensions, indicators, and metrics. At the highest level, the framework captures the broad domains of performance: operational, economic, and sustainability dimensions. The second level refines these dimensions into measurable performance indicators, including cost, efficiency, quality, timeliness, and environmental impacts. These indicators serve a critical bridging function by translating dimensions into operational constructs. The third level operationalises these constructs through specific, quantifiable metrics, such as logistics cost, energy cost, throughput, resource utilisation, process time, waiting time, shelf life, temperature degree hours (TDH), CO_2 emissions, and energy consumption. This hierarchical structure provides conceptual clarity and ensures that the simulation outputs are interpreted within an analytically coherent framework.

The AHP approach enabled the systematic evaluation and prioritisation of these dimensions, indicators, and metrics. Expert judgements were aggregated using the geometric mean method, and internal consistency was validated using Saaty's Consistency Ratio (CR) (Saaty 1980). The synthesis of the AHP results revealed a clear and decision-relevant hierarchy of priorities across the three analytical layers, with all CRs falling well below the conventional 0.10 threshold (CR = 0.033 for dimensions, 0.028 for indicators, and 0.021 for metrics), confirming that expert judgements are internally coherent and that the derived weights warrant interpretive confidence (Table 1). The normalised pairwise comparison matrix and derived priority weights for the performance dimensions assign the highest priority to Operational Performance (w = 0.620), followed by Sustainability Performance (w = 0.270) and Economic Performance (w = 0.110). The AHP also revealed the aggregated priority weights for the five performance indicators. Quality (w = 0.401) and timeliness (w = 0.243) together accounted for 68.5% of the total indicator level weights. Cost (w = 0.136), environmental (w = 0.146), and efficiency (w = 0.074) occupy smaller portions of the expert preference distribution. At the metric level, shelf life (w = 0.232) and TDH (w = 0.184) accounted for 50.7% of the total metric weight. The remaining eight performance metrics shared the remaining 49.3% progressively, from

TABLE 1: Analytic hierarchy process-derived priority weights and ranking of cold chain logistics performance dimensions, indicators, and metrics.

Level	Parameter	Weight	Rank	CR
Dimension	-	-	-	0.033
	Operational performance	0.620	1	-
	Sustainability performance	0.270	2	-
	Economic performance	0.110	3	-
Indicator	-	-	-	0.028
	Quality	0.401	1	-
	Timeliness	0.243	2	-
	Environmental	0.146	3	-
	Cost	0.136	4	-
	Efficiency	0.073	5	-
Metric	-	-	-	0.021
	Shelf life	0.232	1	-
	Temperature degree hours	0.184	2	-
	Waiting time	0.137	3	-
	CO_2 emission	0.105	4	-
	Logistics cost	0.092	5	-
	Resource utilisation	0.088	6	-
	Process time	0.059	7	-
	Energy cost	0.048	8	-
	Energy consumption	0.033	9	-
	Throughput	0.022	10	-

CR, Consistency ratio.

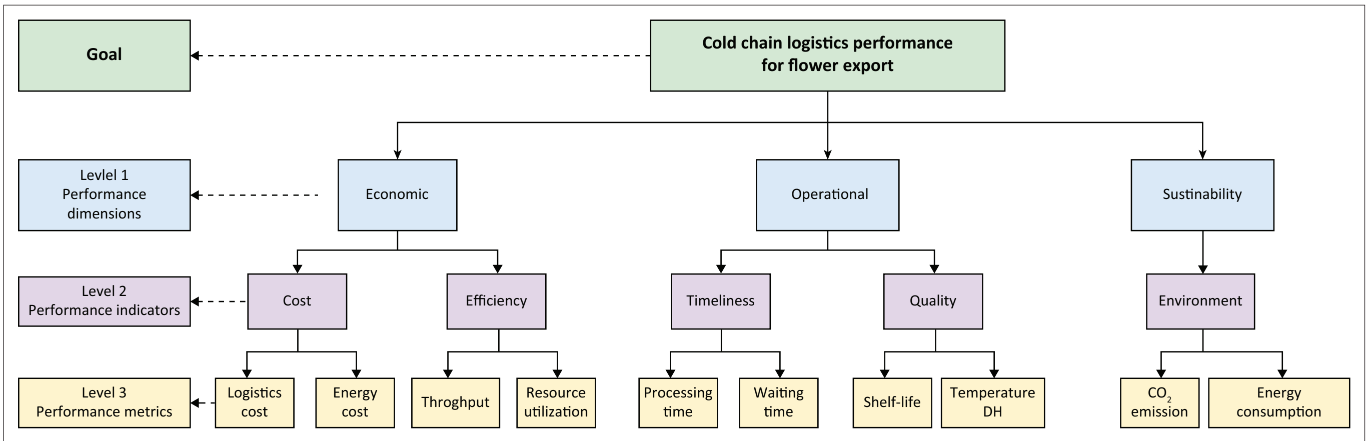


FIGURE 2: Hierarchical performance measurement framework of the study.

waiting time (w = 0.137), CO_2 emissions (w = 0.105), logistics cost (w = 0.092), resource utilisation (w = 0.088), process time (w = 0.059), energy cost (w = 0.048), energy consumption (w = 0.033), and throughput (w = 0.022).

The AHP results show that operational performance received the highest overall weight, indicating that experts view process reliability and product preservation capacity as the main concerns in floriculture logistics. This is relevant in floriculture, where even minor deviations in temperature and delays can degrade quality. At the indicator level, the prioritisation of quality and timeliness reinforces the centrality of the biological preservation process. The quality indicator captures the physiological condition of flowers, whereas timeliness reflects the temporal dimensions of logistics operations. At the metric level, the prominence of shelf life and TDH demonstrates the framework's alignment with the domain-specific performance requirements. These results are theoretically and practically meaningful because they align the performance framework with the biological sensitivity of cut flowers and the time-critical nature of perishable export logistics.

System representation and conceptual modelling

Developing a conceptual model is the initial step in creating an effective DES. According to Robinson (2020), conceptual modelling is the most critical component of simulation studies because it ensures appropriate model complexity. The conceptual model framework for assessing CCL performance in the floriculture industry involves several critical components. This framework integrates theoretical perspectives and empirical data to create a simulation model that effectively evaluates the CCL processes. The framework must account for the characteristics of floriculture products, which are highly perishable and sensitive to temperature fluctuations. The BPMN diagram shown in Figure 3 presents a structured representation of the CCL process for flower export. It is organised into three primary lanes: Market, Grower/Exporter, and Handling Agent. The model captures the end-to-end operational flow by integrating order management, post-harvest handling, refrigerated transportation, quality control, and final deliveries.

Within the Market Lane, the process begins when an order enters a queue for fulfilment. At this level, exceptions such as flowers failing quality inspection, unfulfilled orders, overstayed boxes, and delays associated with high-temperature exposure were explicitly identified. These exception pathways reflect operational risks and performance failures, influencing whether orders are fulfilled. In the Grower/Exporter Lane, the physical flow of flowers begins with the availability of products for harvesting, followed by cutting and post-harvest processing, including packing. The process then reaches an exclusive gateway that evaluates whether the flowers meet the export quality standards.

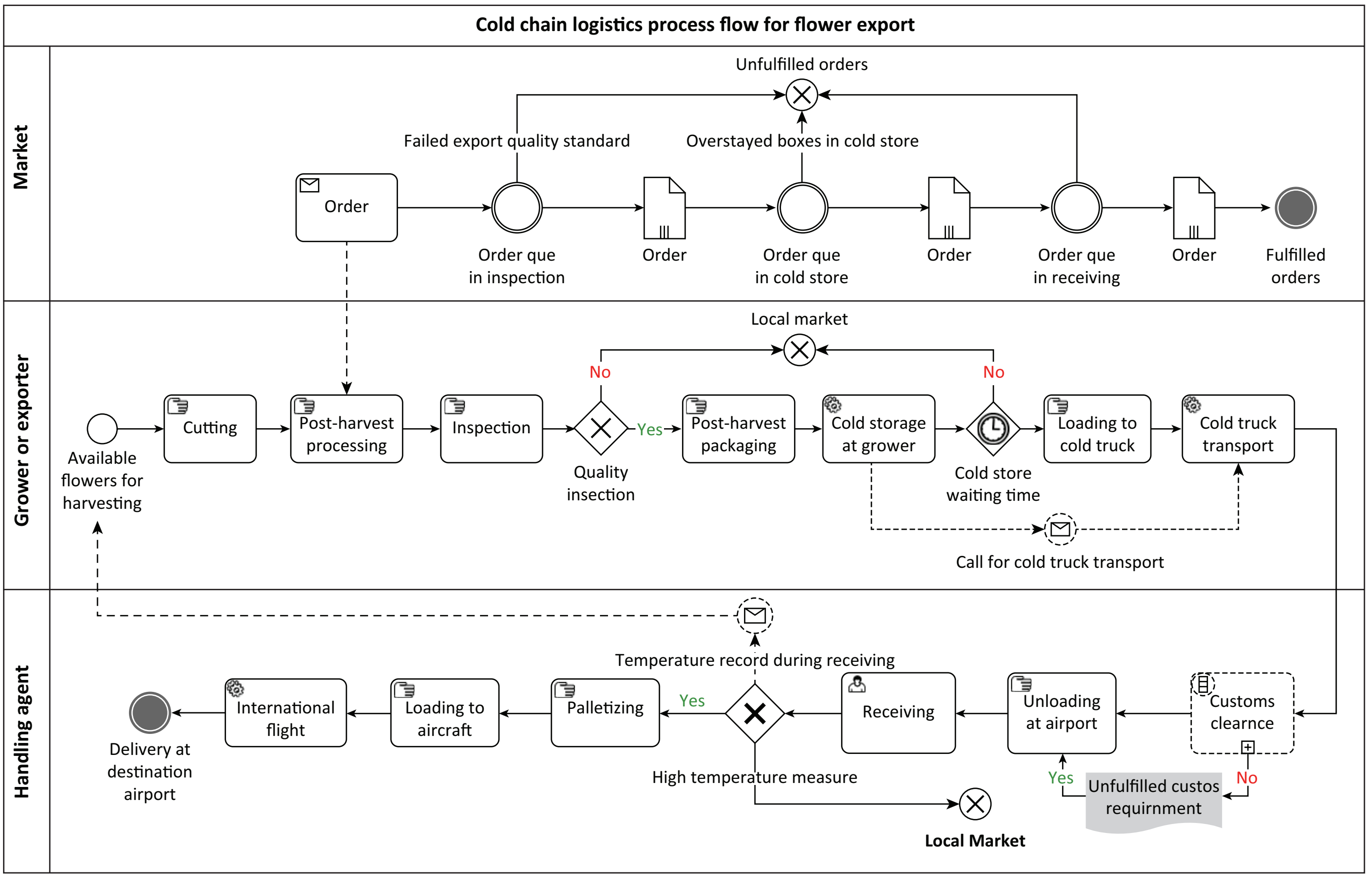


FIGURE 3: Business process notation model of the flower export cold chain logistics system.

The second decision point evaluates the waiting time in the cold storage. Prolonged storage time (more than 48 h) triggers the diversion of flowers to the local market. For the accepted flowers, the process proceeds with loading them onto refrigerated trucks and transporting them to the airport for export. A message flow indicates the coordination required for cold truck services, highlighting the integration of logistics operations across actors. The Handling Agent Lane captures downstream logistics operations at airports and during international transport. Upon the arrival of trucks, a gateway evaluates the timeliness of shipment arrival, where delays result in diversion to the local market. For timely shipments, to ensure regulatory compliance through customs clearance, flower boxes are unloaded and subject to temperature measurements upon receipt. This stage introduces monitoring mechanisms that record temperature conditions and feed information to upstream actors. The process continues through palletising, cold storage, loading, temperature-controlled international flights, and delivery to the destination. The BPMN model integrates material flow, information flow, and control mechanisms. This highlights the interplay between operational efficiency and quality control. The inclusion of multiple gateways and feedback loops underscores the importance of temperature control, process time management, and regulatory compliance in maintaining product quality and ensuring effective cold-chain performance in the floriculture export sector. This presentation provides an important basis for CCL performance analysis by identifying where bottlenecks, delays, and environmental deviations are likely to affect the system. It also demonstrates the value of combining process mapping with simulation, as the conceptual model clarifies the logic and decision structure before stochastic experimentation begins.

Discrete event simulation of flower export cold chain logistics

Discrete event simulation is a valuable tool for analysing and improving the CCL of FAPs. This approach is well-suited for modelling the dynamic and stochastic characteristics of supply chains, enabling decision-makers to evaluate alternative scenarios and strategies (Bhardwaj & Agrawal 2024). Through DES models, product flow within a cold chain can be effectively simulated to identify bottlenecks, evaluate performance, and optimise resource allocation (Zhu et al. 2014). Previous studies have used DES to examine cold chain aspects such as temperature control, transportation, and storage. For instance, a novel route optimisation for the CCL distribution of FAPs was developed using a discrete-event simulation (Jiayang et al. 2018). This approach is particularly useful for analysing the performance of CCL, where the timing and sequence of events are critical for maintaining the quality of perishable products. In practical terms, the model enables comparison of grower-level outcomes across multiple KPI categories while preserving the complexity of the system. An additional strength of the model is its ability to integrate operational and quality variables. Rather than assessing throughput, cost, or temperature in isolation, the model enables determination of how process time, storage exposure, and transportation behaviour interact to influence shelf life, cost, and emissions.

Simulation configuration and model specification

The DES model was configured to replicate the operational behaviour of the flower export CCL under stochastic operating conditions. The configuration integrates operational entities, process logic, stochastic variability, and performance measure structures into a simulation environment. The simulation model was specified using a quantification framework that defines the operational entities, variables, indices, parameters, and performance measurement logic embedded in the DES model. The model specification established a computational framework that transformed shipment-level operational events into measurable performance metrics. It integrates the representation of heterogeneous grower agents, cold chain stages, resource pools, temporal variables, quality degradation parameters, costs, and environmental variables. This specification provides an analytical foundation for the operational equations, replication-level sample functions, and statistical estimation procedures used throughout the performance analysis. Table 2 summarises the variables, domains, and contextual interpretations used in the model.

Following the formal specification of the model variables and operational structure, the performance measurement framework was operationalised through a set of computational equations. The operational equations define how shipment-level performance metrics were computed directly from the DES event logic and then aggregated across independent replications to estimate system-level performance. These quantifications enabled a direct analytical link between simulation events, operational measurements, grower-level outputs, and the comparative results presented in the subsequent analysis section. Table 3 presents the operational formulas and replication-level functions used to quantify throughput, process efficiency, waiting and processing time, quality degradation, logistics costs, energy consumption, and emissions.

Performance analysis of simulation results

Simulation-driven performance analysis of CCL for flower exports offers insights into multiple KPIs. This study examined critical CCL performance metrics, including throughput, processing time, waiting time, logistics operational costs, energy costs, temperature degree-hours, shelf life, energy consumption, and CO_2 emissions. The subsequent discussion addresses the main findings and insights derived from this comprehensive evaluation.

Throughput

The simulation results revealed substantial heterogeneity in the daily throughput, indicating operational disparities across growers. The horizontal bar chart in Figure 4 shows

TABLE 2: Comprehensive variables, domains, and contextual interpretation.

Symbol	Index or variable	Domain or unit	Model context
Structural indices			
g	Grower index	g = 1, 2, …, 8	Eight heterogeneous grower agents
d	Shipment day	d = 1, 2, …, D	D = total shipment days in simulation run time; d indexes the daily cycle
i	Stage index	i = 1, 2, …, 14	Fourteen thermally active cold chain stages
r	Resource pool index	r = 1, 2, …, 9	Nine resource pools throughout the cold chain system
j	Replication index;	j = 1, 2, …, 30	Thirty independent replications simulation run
L_j	Sample function for a metric	j = 1, …, 30	(L_1, L_2, L_3, …, $L_{(30)}$) is statistically independent 30 replication output
Throughput			
$B^{sp}_{(g,d)}$	Shipped boxes	Integer ≥ 0	Shipped boxes by grower g and exit the model sink on day d
M_j	Total boxes shipped	$M_j = \sum_{g=1}^{8} TH_{g,j}$	Total boxes shipped across all eight growers in replication j
Time variables			
$T_{(entry,g,d)}$	Entry time	Hours	Record clock time when grower g's box enters the system on day d at source block that initialises the total process time counter for each box entity
$T_{(exit,g,d)}$	Exit time	Hours	Record clock time when grower g's box exits at sink block on day d used to compute total process time for each box entity
$T_{(start/finish,i,g,d)}$	Start and finish time	Hours	Record clock time when grower g's box day d on Enter and Exit hooks of each service block; used to compute stage process time
$t_{(i,g,d)}$	Stage dwell time	$t_{(i)} = PT_{(i)} + WT_{(i)}$ [h]	Total dwell time at stage i, including process time and waiting time
Quality and thermal			
$Temp_{(i,g,d)}$	Stage temperature	°C	Box temperature (°C) at stage i for grower g's days d
$SL_{(initial)}$	Initial shelf life	Hours	Total shelf life at harvest
SC	Shelf life Coefficient	h / (°C·hr)	Calibrated by temperature degree hours shelf life degradation model
Cost			
$C_{(lb,tr,stg,hnd,flt)}$	Individual cost	Currency	Labour cost, freight cost per cold truck, unloading cost per truck, handling and flight freight cost per kg
P_e	Energy price	Currency / kWh	Electricity price per kWh and fuel price per litre
Environmental			
E_g	Total energy consumed	kWh	Total energy consumed by grower across stages (cooling and facility ambient load across farm cold storage, transport, receiving, palletising, airport cold storage, flight)
EF	Emission factor	kg CO_2 / kWh	CO_2 intensity of fuel and grid electricity of energy consumed across stages

that Grower 6 achieved an average of 4870 boxes per day, approximately six times that of the other growers, thereby demonstrating substantial economies of scale. In contrast, Grower 7 recorded the lowest throughput at 201 boxes per day, indicating a limited operational capacity. The remaining six growers clustered between 548 and 835 boxes per day with moderate variability. This finding highlights the strong heterogeneity in throughput performance across growers, indicating unequal operational capacity within the system. The box plot visualisation highlights the exceptional performance of the Grower 6. The high throughput was accompanied by considerable variability (standard deviation [s.d.] of 338.9) and a wide range (4088–5322 boxes), suggesting underlying fluctuations due to demand variability. Grower 7 exhibited the lowest throughput at 201 boxes per day, with minimal variability (s.d. of 19.4), underscoring a consistent yet limited operational capacity. The intermediate growers (Growers 1, 3, 4, 5, and 8) displayed relatively homogeneous throughput levels (730–835 boxes per day) with moderate consistency (s.d. ranging from 51.9 to 101.4 boxes). Grower 2 demonstrated a middle-lower throughput with moderate variability (548 boxes per day, s.d. = 70.5). These insights indicate that growers with high throughput leverage economies of scale, thereby enabling enhanced market penetration and cost efficiencies. Conversely, growers operating on smaller scales must evaluate their operational strategies by considering expansion or efficiency improvements to increase market relevance.

Process time

The process time is the total operational time from when a flower box entity is generated at the source block to when it exits the system at the sink block in the simulation model. It encompasses every stage of the cold chain without exception, representing the total time each box spends in the integrated cold chain system. The total process time, as a performance measure, is computed per box. The analysis examined the process time of CCL among growers. The box plot in Figure 5 shows significant variation, with Grower 2 as a distinct outlier, showing the highest mean time (44.84 h) and a high variability (s.d. of 2.32). This suggests operational inefficiencies in process management and capacity planning. Grower 7 had the lowest mean process time (41.85 h), indicating efficient operations, whereas Grower 6 demonstrated the most consistent timing (s.d. of 0.23 h), indicating well-standardised operations. This consistency benefits supply chain responsiveness and customer satisfaction. Most growers' process times clustered between 41.8 h and 42.3 h, except for Grower 2, highlighting the need for operational improvements. These findings emphasise the importance of stable process management for operational excellence. Process time consistency, as shown by Grower 6, improves performance across operational dimensions in the floriculture CCL. The bar chart shows the mean total process time per grower, with standard deviation. Grower 2's high mean time (44.84 h) and variability identified it as an outlier, requiring operational improvements. Other growers maintained

TABLE 3: Operational performance metric quantification and computation.

Metric	Unit	System-level operational computation	Grower-level operational computation
Throughput	Boxes	$\mathrm{TH}_g = \sum_{d=1}^{D} B^{\mathrm{sp}}_{g,d}$	$L^{\mathrm{TH}}_j = \sum_{g=1}^{8} \mathrm{TH}_{g,j}$
Average daily throughput	Boxes	$\mathrm{TH}_g = \frac{1}{D}\sum_{d=1}^{D} B^{\mathrm{sp}}_{g,d}$	$\mathrm{L}^{\mathrm{TH}}_j = \frac{1}{8}\sum_{g=1}^{8} \mathrm{TH}_{g,j}$
Total process time	Hours	$\mathrm{TPT}_{g,d} = \mathrm{T}_{\mathrm{exit},g,d} - \mathrm{T}_{\mathrm{entry},g,d}$	$\mathrm{L}^{\mathrm{TPT}}_j = \frac{1}{M_j}\sum_{g,d} \mathrm{TPT}_{g,d,j}$
Stage process time	Hours	$\mathrm{PT}_{i,g,d} = \mathrm{T}_{\mathrm{finiah},i,g,d} - \mathrm{T}_{\mathrm{start},i,g,d}$	$L^{\mathrm{PT}_i}_j = \frac{1}{M_j}\sum_{g,d} \mathrm{PT}_{i,g,d,j}$
Total waiting time	Hours	$\mathrm{TWT}_{g,d} = \sum_{i=1}^{14} \mathrm{WT}_{i,g,d}$	$\mathrm{L}^{\mathrm{TWT}}_j = \frac{1}{M_j}\sum_{g,d} \mathrm{TWT}_{g,d,j}$
Waiting time share	%	$\mathrm{WTS}_{g,d} = \frac{\mathrm{TWT}_{g,d}}{\mathrm{TPT}_{g,d}} \times 100$	$L^{\mathrm{WTS}}_j = \frac{1}{M_j}\sum_{g,d} \mathrm{WTS}_{g,d,j}$
Temp degree-hours	°C h	$\mathrm{TDH}_{g,d} = \sum_{i=1}^{14} \mathrm{Temp}_{i,g,d} \times t_{i,g,d}$	$L^{\mathrm{TDH}}_j = \frac{1}{M_j}\sum_{g,d} \mathrm{TDH}_{g,d,j}$
Shelf life consumed	Hours	$\mathrm{SLC}_{g,d} = \sum_{i=1}^{14} \mathrm{SLC}_{i,g,d}$	$L^{\mathrm{SLC}}_j = \frac{1}{M_j}\sum_{g,d} \mathrm{SLC}_{g,d,j}$
Total logistics cost	Currency	$\mathrm{LC}_g = \mathrm{C}_{lb} + \mathrm{C}_{tr} + \mathrm{C}_{stg} + \mathrm{C}_{hng} + \mathrm{C}_{flt}$	$L^{\mathrm{LC}}_j = \frac{1}{M_j}\sum_{g=1}^{8} \mathrm{LC}_{g,j}$
Logistics cost per box, per day	Currency	$\mathrm{LCB}_g = \frac{\mathrm{LC}_g}{B^{sp}_g}$	$L^{\mathrm{LCB}}_j = \frac{1}{8}\sum_{g=1}^{8} \mathrm{LCB}_{g,j}$
Energy cost	Currency	$\mathrm{EC}_g = E_g \times P_e$	$L^{\mathrm{EC}}_j = \frac{1}{M_j}\sum_{g=1}^{8} \mathrm{EC}_{g,j}$
Energy cost per box	Currency	$\mathrm{ECB}_g = \frac{\mathrm{EC}_g}{B^{sp}_g}$	$L^{\mathrm{ECB}}_j = \frac{1}{8}\sum_{g=1}^{8} \mathrm{ECB}_{g,j}$
Energy consumption per box	kWh	$\mathrm{EPB}_g = \frac{E_g}{B^{sp}_g}$	$L^{\mathrm{EPB}}_j = \frac{1}{8}\sum_{g=1}^{8} \mathrm{EPB}_{g,j}$
Total CO_2 emissions	kg CO_2	$\mathrm{CO}_{2g} = E_g \times \mathrm{EF} + \sum_{d} \mathrm{CO}^{\mathrm{fuel/elec}}_{2g,d}$	$L^{\mathrm{CO_2}}_j = \frac{1}{M_j}\sum_{g=1}^{8} \mathrm{CO}_{2g,j}$
CO_2 emissions per box	kg CO_2	$\mathrm{CO_2PB}_g = \frac{\mathrm{CO}_{2g}}{B^{sp}_g}$	$L^{\mathrm{CO_2PB}}_j = \frac{1}{8}\sum_{g=1}^{8} \mathrm{CO_2PB}_{g,j}$

lower mean times of approximately 42 h, with Grower 7 having the lowest at 41.85 h, demonstrating stable operational practices. These findings suggest that Grower 2 requires targeted improvements in process management and standardised procedures, whereas the other growers exhibit better operational performance.

Figure 6 reveals substantial variations in the waiting time share, indicating differences in process synchronisation and resource utilisation. Grower 2 shows a significantly higher proportion of waiting time than the system average, indicating a bottleneck or inefficiency in flow coordination. Growers 5 and 8 had the lowest shares of waiting time, indicating more streamlined operations. This variability highlights the waiting time as a key performance differentiator across growers.

Cost

The bar chart (Figure 7) presents the average logistics cost per box among the growers, revealing significant disparities in cost efficiency. Grower 6 demonstrated the most cost-effective performance at $14.42 per box, below the overall average of $17.17. This advantage likely results from economies of scale, efficient processes, and optimised resource utilisation. Conversely, Grower 7 incurred the highest logistics cost at $21.67 per box, indicating potential operational inefficiencies, such as underutilised transport capacity and fragmented handling processes. Growers 2, 4, and 3 also operated above the average cost threshold, suggesting opportunities for further improvement. Logistics costs are closely linked to operational efficiency and throughput scale. Growers with higher costs must reassess their supply chain configurations and load-consolidation strategies. Strategic investments in logistics planning and digital monitoring tools can reduce costs and enhance their competitiveness. This study identified significant cost disparities that reflect operational efficiency gaps. Grower 6 incurred the lowest logistics cost per box ($14.42), reflecting operational efficiency. Conversely, Grower 7 incurred the highest logistics costs ($21.67 per box), suggesting inefficiency. Operational consistency, demonstrated by Grower 6's low variability, underscores process optimisation as a key factor for competitiveness. Energy cost analysis revealed substantial differences linked to throughput volumes. Despite Grower 6's high total energy costs owing to its larger scale, the per-box energy cost remained competitive at $8.54 per box. Grower 2 achieved the lowest energy cost per box ($7.66), demonstrating trade-offs between scale, efficiency, and energy consumption.

Temperature degree hours

Temperature degree hours, also known as the degree days model when expressed in days, measures the effects of temperature and time on cut flowers. It is calculated as the product of temperature in degrees Celsius and exposure time in hours or days, accumulated over the logistics process (De Kok 2009; Harkema et al. 2017). In the floriculture sector, particularly for cut flowers, TDH helps predict shelf life reduction as a function of temperature. It provides a simplified and operationally useful method for monitoring CCL performance and predicting quality degradation (Van Meeteren 2008). Figure 8 shows considerable variability in TDH among growers over the course of the shipment days. Notably, Grower 2 exhibited significant inconsistency and elevated average temperature exposure, indicating substantial deficiencies in the temperature management practices. This variability (s.d. = 35.18) underscores the severe risk of quality deterioration and reduced shelf life. In contrast, Growers 5, 4, and 8 demonstrated stable and effective temperature control, as evidenced by minimal fluctuations (s.d. of approximately 3). This stability directly correlates with enhanced product quality preservation and extended shelf life, which are crucial for maintaining a competitive

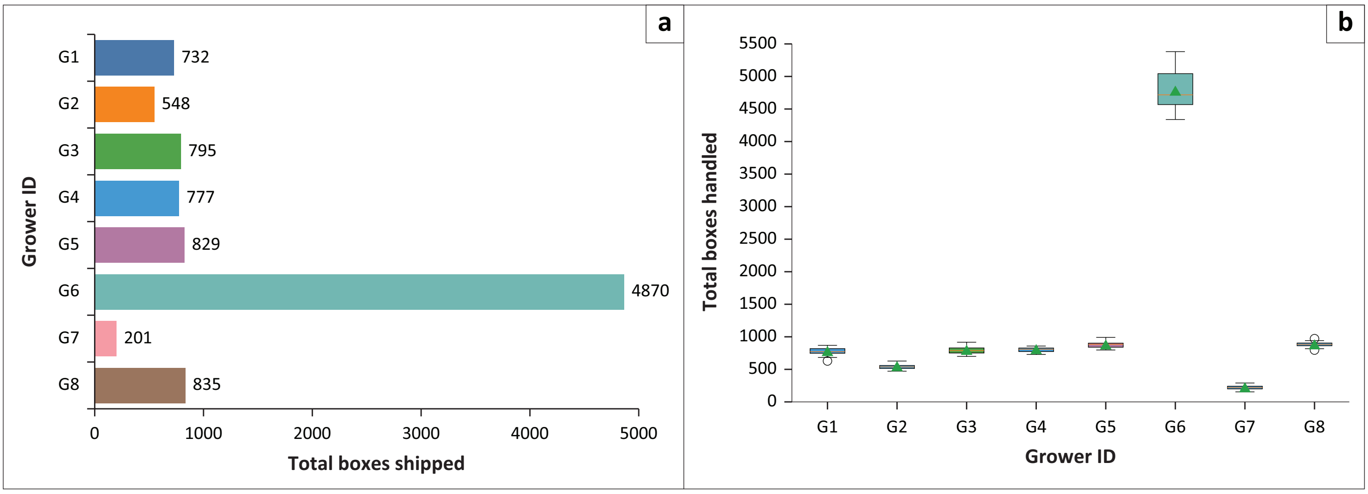


FIGURE 4: Total boxes shipped and variability across growers: (a) Total boxes shipped; (b) Total boxes handled.

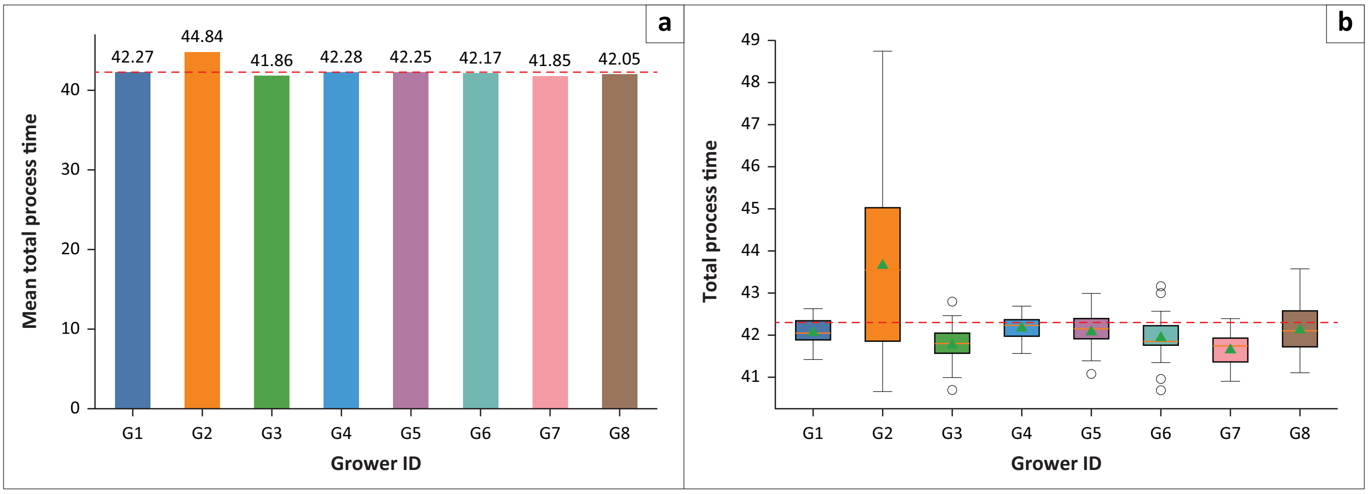


FIGURE 5: Mean total process time and variability across growers: (a) Mean total process time; (b) Total process time.

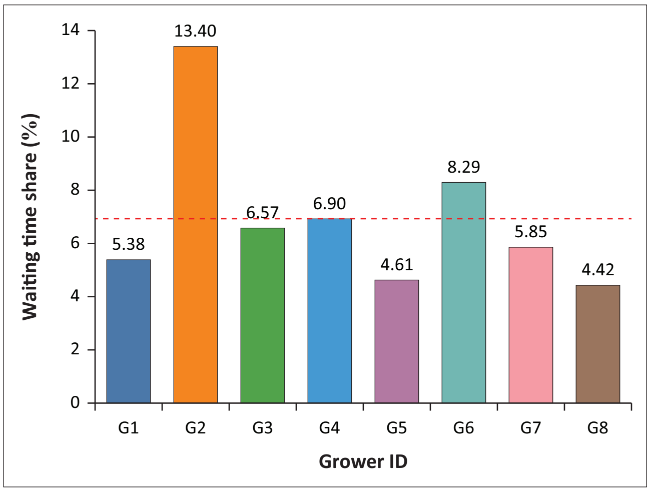


FIGURE 6: Waiting time as a share of total process time across growers.

advantage in the export market. These findings highlight the urgent need for growers, such as Grower 2, to improve their cold chain infrastructure, adopt robust temperature monitoring systems, and standardise operational protocols. TDH, a critical determinant of quality in cold chains, varies widely among growers. Grower 6 demonstrated better temperature management, with the lowest TDH, indicating efficient cold chain infrastructure and practices. Conversely, Grower 2, with the highest TDH and substantial variability, faced significant quality risk. These insights underscore the essential role of precise temperature control systems in maintaining product integrity and competitiveness in the industry.

Consumed shelf life

The consumed shelf life closely paralleled the TDH results, highlighting the correlation between temperature management and product quality. Grower 6 exhibited better cold chain effectiveness, as evidenced by its lowest average consumed shelf life. In contrast, Grower 2 demonstrated a significantly higher depletion of shelf life, indicating inefficiency and suboptimal temperature management. Consequently, investing in effective cold chain practices directly enhances product shelf life and reduces waste. The heat map (Figure 9) illustrates clear disparities in shelf life consumption among growers across multiple shipment days. Grower 6 demonstrated the best performance, with the lowest average shelf life (13.73 h), indicating highly efficient cold-chain management and minimal exposure to temperature deviations. In stark contrast, Grower 2 performed the worst, with an average shelf life consumption

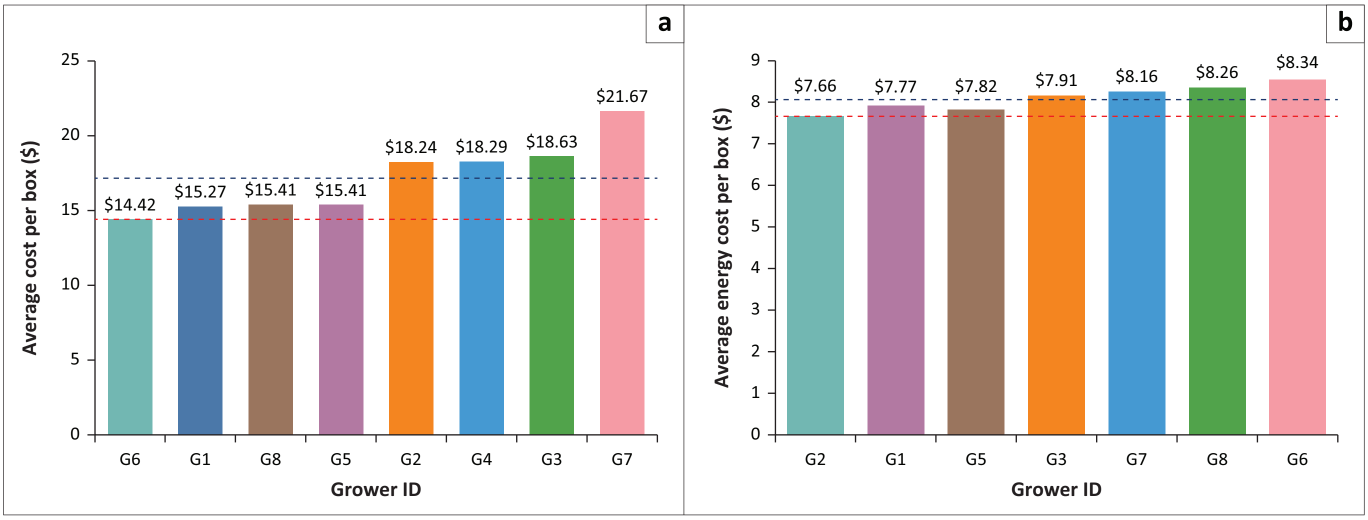


FIGURE 7: Average logistics operations cost and energy cost per box across growers: (a) Average cost per box ($); Average energy cost per box ($).

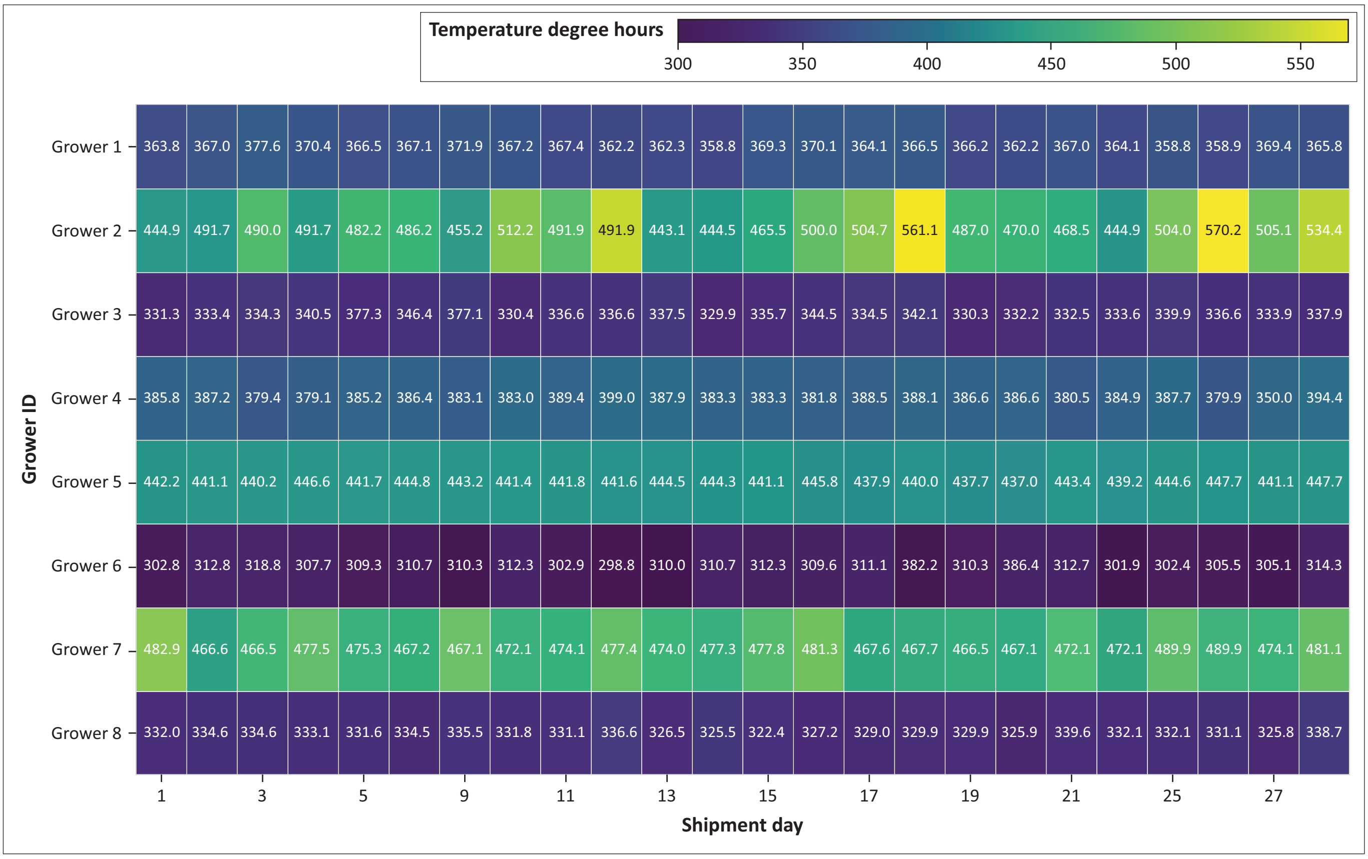


FIGURE 8: Temperature degree hours across growers by shipment day.

of 22.55 h, approximately 64% higher than that of Grower 6. The heatmap shows significant fluctuations and peaks (up to 26.97 h), revealing inconsistent handling and probable cold-chain breaks. Shelf life is a direct proxy for cold-chain effectiveness and final product quality. Growers with poor performance risk reduced flower freshness, higher rejection rates, and diminished customer satisfaction.

Energy consumption and CO_2 emission

The analysis (Figure 10) showed that the flight stage accounted for 97.8% of the energy consumption, with cold truck transportation contributing 2.2%. This highlights the need for sustainable interventions in air transportation, such as enhancing cargo efficiency, deploying energy-efficient aircraft, and exploring alternative transportation methods to reduce the energy footprint. The study found significant variations in CO_2 emissions among the growers, reflecting differences in operational practices, transportation efficiency, and scale. Given the impact of air transport, growers need improvements in load optimisation, energy-efficient practices, and the potential adoption of alternative fuels to reduce their

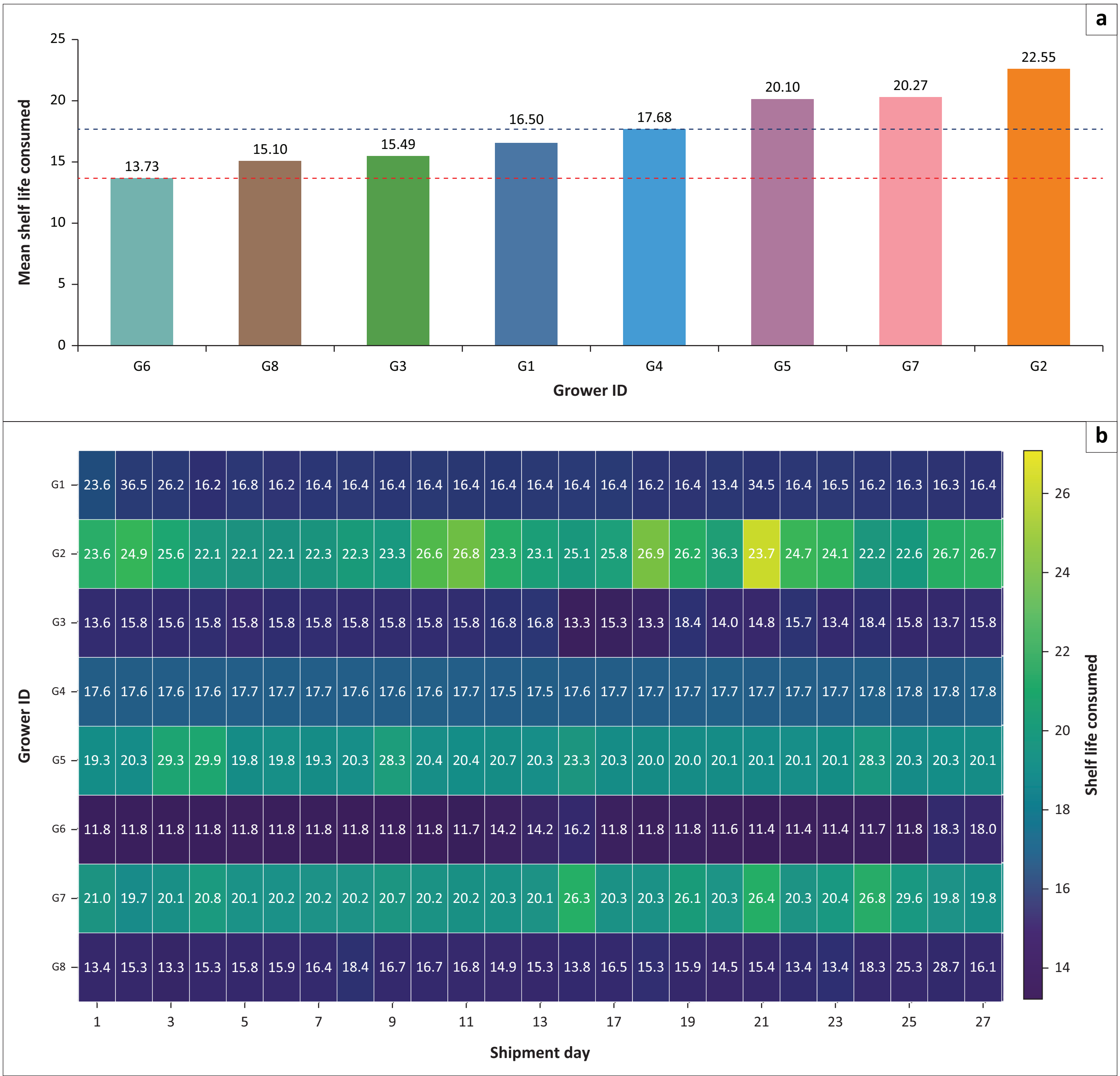


FIGURE 9: Mean shelf life consumed across growers by shipment day: (a) Mean shelf life consumed; (b) Shelf life consumed per shipment day.

carbon footprint. The bar chart shows the average CO_2 emissions per box across growers, revealing significant performance differences. The overall average emission was 10.20 kg CO_2 per box. Grower 6 had the highest average CO_2 emissions (13.27 kg CO_2), exceeding the industry average. This elevated figure is related to large-scale operations and higher logistics activities, particularly in air transport. Although Grower 6 excels in throughput, shelf life management, and cost efficiency, this indicates a trade-off with environmental sustainability. Growers 2, 4, and 5 reported the lowest emissions (9.02 kg CO_2 – 9.43 kg CO_2), indicating more environmentally efficient operations. High throughput can increase emissions unless it is matched with sustainability measures. Improving CO_2 efficiency is critical for meeting global sustainability standards and low-carbon supply chain requirements in the international markets. Integrating environmental performance into operations is essential for the long-term competitiveness of the floriculture industry.

Trade-off among key performance indicators

The interaction of different KPIs provides important insights into the trade-offs in managing CCL. The radar chart (Figure 11) presents a normalised comparison of the KPIs across the growers, capturing the operational, economic, and environmental dimensions simultaneously. Good-performing growers, such as Grower 6, have improved throughput, maintained high quality with good temperature control, and reduced logistics costs. However, these successes have also led to increased energy use and

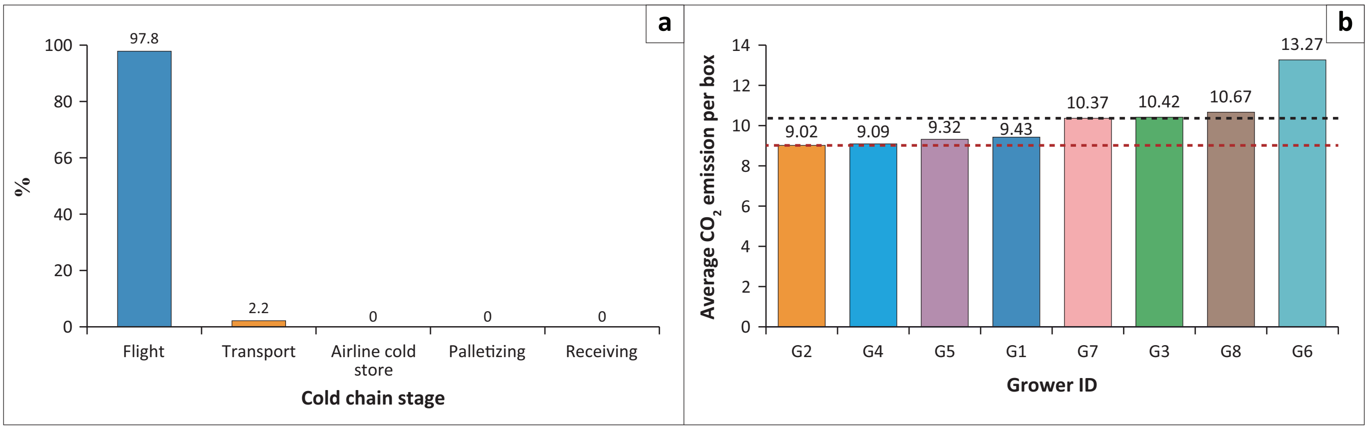


FIGURE 10: Percentage contribution of cold chain stages to total energy consumption and average kg CO_2 emissions per box across growers.

environmental impacts, highlighting the challenges associated with scaling operations. In contrast, growers with lower throughput, such as Growers 7 and 2, used less energy but had worse quality control, higher logistics costs, and inefficient operations, thereby affecting their economic viability and competitiveness.

Clear variations were observed across multiple metrics, indicating trade-offs in performance. Some growers exhibit strong performance on cost-related indicators but weaker outcomes on environmental metrics such as CO_2 emissions and energy use. Notably, no single grower dominated across all indicators, highlighting multi-objective trade-offs within the cold chain system. This pattern supports the need for integrated performance evaluation and optimised approaches that simultaneously consider the cost, efficiency, and sustainability. The visualisation further emphasises the heterogeneity in growers' performance, suggesting opportunities for targeted improvements and benchmarking against the best-performing peers.

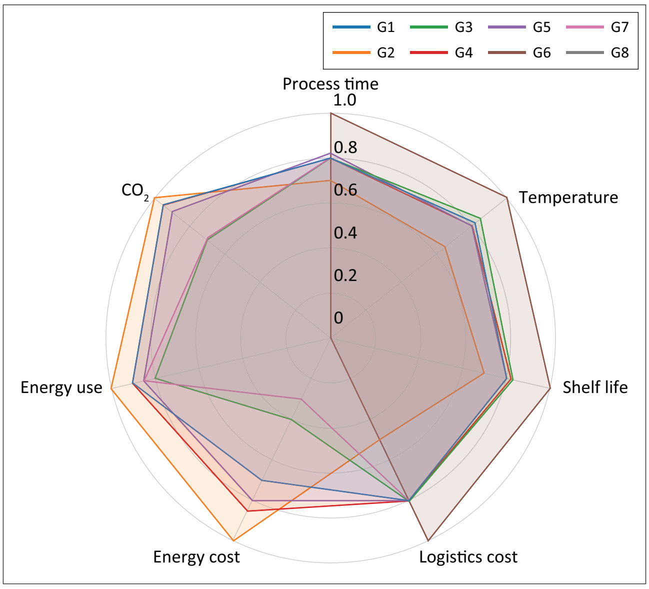


FIGURE 11: Radar chart comparing normalised performance indicators across growers.

Conclusion and recommendations

This study developed and applied a simulation-driven framework for the performance analysis of the export flower CCL in the Ethiopian floriculture industry. By integrating a literature review, expert-based evaluation and prioritisation, AHP, conceptual modelling, and DES, this study provides an integrated method for evaluating CCL performance across operational, economic, and sustainability dimensions.

The findings reveal notable operational disparities across growers in terms of throughput, process efficiency, temperature management, shelf life preservation, costs, and environmental impact. Large-scale operations can achieve higher throughput and lower logistics costs per box; however, these advantages do not necessarily translate to better environmental performance.

Quality-related outcomes, especially TDH and shelf life consumption, differ markedly across growers and are shaped by temperature management and process stability. The results also showed that the air transport stage is the dominant contributor to overall energy use and emissions, highlighting the environmental sensitivity of export-oriented floriculture logistics. These variations highlight the need for tailored interventions and strategic optimisation to enhance overall CCL performance. The study's findings also emphasise the inherent trade-offs among different KPIs, necessitating a balanced and integrated management approach. Higher operational scales and efficiencies often lead to increased absolute energy consumption and CO_2 emissions, posing significant sustainability challenges.

Based on the key findings, the following recommendations is proposed: Growers should benchmark and implement standardised operational procedures, as exemplified by top-performing growers. This should focus on streamlining processes, minimising waiting and processing times, and optimising resource utilisation. Significant investments in advanced temperature-controlled infrastructure and precise monitoring technologies should be considered. Such interventions can substantially enhance product quality, extend shelf life, and reduce product wastage. Encouraging economies of scale through strategic alliances, collaborations, or resource pooling among growers can significantly decrease logistics and energy costs per unit, thereby improving the economic efficiency and global market competitiveness of the industry.

Targeted improvements, particularly in the air transport stage, such as optimising cargo loading and incorporating sustainable fuel alternatives, are critical for mitigating significant environmental impacts. Enhancing responsiveness through improved operational planning, real-time communication technologies, and effective logistical coordination can significantly improve market responsiveness and reduce operational inefficiency. Employing simulation-based optimisation tools and continuous performance monitoring systems will provide growers and policymakers with data-driven insights, facilitating informed strategic decision-making and comprehensive performance management. More broadly, industry leaders should adopt simulation-supported decision-making tools to test operational alternatives before implementation.

This study has several limitations. It is based on a specific national context and a limited set of empirical cases. The prioritisation of performance parameters and AHP weights reflects the priorities of Ethiopian experts, which may vary in different economic or cultural contexts. Additionally, the reported analysis focuses primarily on the baseline system behaviour rather than scenario analysis. The simulation model does not represent upstream agricultural variability in crop yield, post-harvest quality, or downstream retail handling. Future research should extend the model to include upstream and downstream variability, incorporate IoT sensor data streams to enable dynamic simulation, apply multi-objective optimisation, such as non-dominated sorting genetic algorithm II (NSGA-II), to resolve the identified trade-offs, and conduct comparative cross-country analyses to support adaptive cold chain systems.

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During the preparation of this work, the authors used Grammarly to improve the language clarity, grammar, and punctuation. All content was carefully reviewed by the authors, who accept full responsibility for its accuracy.

Competing interest

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

CRediT authorship contribution

Abadi A. Gugusa: Conceptualisation, Data curation, Formal analysis, Methodology, Software, Validation, Visualisation, Writing – original draft. Dante B. Matellini: Conceptualisation, Supervision, Writing – review & editing. Chia-Hsun Chang: Conceptualisation, Supervision, Writing – review & editing. Ian Jenkinson: Conceptualisation, Supervision, Writing – review & editing. All authors reviewed the article, contributed to the discussion of results, approved the final version for submission and publication, and take responsibility for the integrity of its findings.

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Data availability

The data collected from experts, including evaluation inputs, AHP pairwise comparisons, simulation model parametrisation data, and raw shipment records, are available from the corresponding author upon request, subject to the confidentiality agreements made with participating growers, transporters, and handling agents.

Disclaimer

The views and opinions expressed in this article are those of the authors and are the product of professional research. They do not necessarily reflect the official policy or position of any affiliated institution, funder, agency, or that of the publisher.

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