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# Optimization of fruit and vegetable logistics in the Port of Valparaíso, Chile, through strategic logistics platforms and blockchain technology

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***Abstract:*** This study addresses optimizing the fruit and vegetable logistics chain at the Port of Valparaíso, Chile, a key hub for exports in the Southern Hemisphere. Through an integrated approach, it combines logistics platforms (in Limache and Quillota), blockchain technology, and a Capacitated Facility Location Problem (CFLP) mathematical model. These tools help mitigate traffic congestion, high logistics costs, and limited traceability, achieving up to a 25% savings in operating expenses, a 30% reduction in $CO_2$ emissions, and a 50% decrease in waiting times. Integrating blockchain ensures immutable records, improving supply chain trust and the quality of exported products. This proposal, aligned with Industry 5.0 principles, promotes economic resilience and sustainability, positioning the Port of Valparaíso as an international benchmark for logistics innovation. The framework can be replicated in other ports, contributing to more efficient and sustainable supply chains and reducing urban congestion. Finally, the paper discusses social and political risks associated with infrastructure development, compares MILP with other optimization methods (heuristics or metaheuristics), and expands on the model's potential application to different ports, including dry ports or those with limited capacity.

## 1 Introduction

The Port of Valparaíso manages about 70% of Chile's fruit and vegetable shipments [1], making it critical for international trade in the Southern Hemisphere. Nevertheless, it faces operational challenges such as congested road access, elevated logistics costs, and lagging adoption of advanced technologies, all of which undermine port competitiveness and sustainability. An integrated solution harmonizes global economic, social, and environmental considerations, where greater efficiency, traceability, and environmental responsibility are increasingly demanded [2].

This article proposes a holistic strategy encompassing:

1. Strategic logistics platforms situated in Limache and Quillota.
2. Blockchain technology to ensure full traceability and secure data exchange.
3. A mathematical model (CFLP) formulated via mixed-integer linear programming (MILP).

The approach aims to reduce costs by 25%, cut waiting times by 50%, and lower $CO_2$ emissions by 30%, thereby enhancing the competitiveness of fruit and vegetable exports. Blockchain and IoT integration support data security and product quality. This proposal is grounded in Industry 5.0, which emphasizes the synergy of humans and intelligent systems to achieve competitiveness and sustainability. Following a discussion of the literature, we detail the methodology (including a comparative analysis of MILP and heuristic methods), present our results, and examine the replicability in other ports—maritime or inland—and the social and political risks that can affect implementation.

## 2 Literature review

### 2.1 Innovation and improvement in logistics chain management

Technological innovation has become essential for improving competitiveness in seaport supply chains with significant seasonal demand. Tools such as artificial intelligence (AI), the Internet of Things (IoT), and blockchain have reshaped cargo handling by minimizing human errors and enhancing transparency. Automation solutions (e.g., collaborative robots) yield greater accuracy in loading/unloading tasks, while digitalization (e.g., TradeLens) enables real-time, data-driven decisions, reducing costs and processing times. Leading seaports with advanced logistics (e.g., Rotterdam, Singapore) have achieved substantial operational efficiency through such technologies [3].

### *2.2 Blockchain in logistics*

Blockchain technology provides immutable records and decentralized ledgers, strengthening traceability and document security in supply chains. For instance, adopting blockchain-based platforms in the Port of Rotterdam reduced document processing times by up to 80% [4]. At Valparaíso, blockchain offers reliable quality verification for horticultural products (which is crucial for high-standard markets), facilitating expedited approvals and enhanced data security. Convergence with AI-based forecasting or real-time route management also increases supply chain resilience and transparency [5].

### *2.3 Industry 5.0 and digital transformation*

Industry 5.0 emphasizes human-machine collaboration with a focus on sustainability and service personalization. In a port environment, this merges AI, IoT, blockchain, and automation, keeping humans at the core to make strategic decisions while repetitive tasks are delegated to intelligent systems. Besides operational efficiency, resilience in disruptions and a reduced environmental footprint are central goals—vital for seaports with high shipping volumes, including Valparaíso [6].

### *2.4 Mathematical model and location of facilities*

The Capacitated Facility Location Problem (CFLP) is a mixed-integer linear programming model that finds the optimal location for facilities subject to capacity constraints and demand. Studies in port settings have demonstrated cost reductions of around 12% and efficiency gains of around 18% when applying the CFLP [7]. For Valparaíso, placing logistics platforms in Limache and Quillota—integrating road and rail—helps reduce congestion and total costs.

Nonetheless, alternative methods, such as heuristics or metaheuristics (e.g., genetic algorithms, ant colony optimization, tabu search), can swiftly tackle large-scale problems but often lack guaranteed global optimality. Meanwhile, the MILP approach ensures robust, exact solutions, although potentially at a higher computational cost. For Valparaíso, where problem size is moderate and infrastructure decisions are financially significant, the thorough analysis and guaranteed optimality offered by MILP outweigh the benefits of faster but approximate methods. In very large or highly uncertain settings, hybrid schemes that blend MILP with heuristic search could be explored, but in the present case, MILP on it remains sufficient and advantageous [8].

### *2.5 Port logistics and sustainability*

Sustainability is becoming a key objective in the port logistics industry, in alignment with the Paris Agreement and the Sustainable Development Goals (SDGs). Redesigning logistical networks and setting up inland platforms (dry ports) effectively reduces $CO_2$ emissions, congestion, and direct truck traffic in sensitive urban areas. This approach also helps address social aspects: less congestion improves the quality of life for residents near major gateways. Digitization and multimodal integration raise energy efficiency and traceability, making "green logistics" a competitive advantage. Chile's modernization plans for port infrastructure and climate change commitments further support environmentally responsible strategies, such as those proposed for Valparaíso [9].

### *2.6 Contextualization and regulatory challenges*

The Port of Valparaíso is strategically situated for Chile's international trade. However, the port's competitiveness faces complex regulatory challenges, such as integrating international regulations in logistics, the implementation of environmental policies, and digitalizing operational processes. Current rules require ports to adopt sustainable standards aligned with the Sustainable Development Goals (SDGs), especially in reducing carbon emissions and promoting renewable energy [10].

On the other hand, implementing blockchain technology in the port requires a regulatory framework that guarantees the interoperability of systems and data protection. According to ECLAC (2021) [3], regulatory challenges include defining global standards for data exchange and collaboration between regional public and private actors. For Valparaíso, this implies advancing bilateral agreements with key trading partners and adapting port infrastructure to international regulations such as the Paris Agreement and the World Trade Organization (WTO) trade transparency frameworks.

Current regulations increasingly require ports to meet sustainable-development standards, especially on carbon-reduction targets and promoting renewable energy. Implementing blockchain at Valparaíso also demands a legal framework that guarantees system interoperability and data protection; establishing global data-exchange standards and fostering public-private collaboration are therefore critical. For Valparaíso, progress hinges on bilateral agreements with key trading partners and adapting port infrastructure to international frameworks such as the Paris Agreement and WTO transparency rules [11].

## 3 Methodology

### *3.1 Study design*

This paper follows an applied, multidisciplinary approach:

1. Diagnostic: Gathering data on congestion, costs, and traceability issues in Valparaíso to identify bottlenecks and opportunities [12].
2. Objectives: Lower costs by 25%, cut emissions by 30%, and reduce waiting times by 50%.
3. MILP (CFLP) model: Locate platforms (Limache, Quillota) and assign traffic flows in a multimodal context [13].
4. Blockchain integration: Provide end-to-end supply chain transparency and data security [14].
5. Validation and sensitivity: Compare baseline vs. optimized scenarios under various demand or cost changes (+15% demand, ±20% fuel costs), referencing similar international port examples [15].

The model used is based on the mathematical model proposed by Chen & Ting [16], known as the Capacity Constrained Facility Location Problem (CFLP). This approach aims to minimize the total transportation and location cost, determining the optimal number and location of facilities and allocating demand to each. In other words, it looks at how many responsive logistics centers are needed and where they should be located to minimize costs without exceeding their capacity.

The CFLP formulation is the objective function (1):

$$\boldsymbol{Min\ Z = \sum_i^n \sum_j^m C_{ij} X_{ij} + \sum_j^m f_j y_J} \quad (1)$$

Constraints (2)-(7):

$$\boldsymbol{\sum_j^m X_{ij} = 1, \forall i} \quad (2)$$

$$\boldsymbol{\sum_i^n d_i X_{ij} \leq S_i Y_j, \forall j} \quad (3)$$

$$\boldsymbol{\sum_j^m S_i Y_j \geq \sum_{i=1}^n d_i} \quad (4)$$

$$\boldsymbol{X_{ij} \leq Y_j \ \forall i} \quad (5)$$

$$\boldsymbol{Y_j = \{0.1\}} \quad (6)$$

$$\boldsymbol{X_{ij} = \{0.1\}} \quad (7)$$

Equation (1) is the function to be minimized and corresponds to the total supply costs, i.e., the costs of meeting the demand when a candidate plant is opened, plus the total fixed costs of locating said plant. Constraint (2) means that each customer is supplied by only one plant; constraint (3) guarantees that the opened plant has sufficient capacity to meet the assigned demand; constraint (4) ensures that the total number of open plants covers the total demand of the area; constraint (5) indicates that if any candidate plant j is opened, it may or may not serve customer i; if it is not opened, it would not be possible to serve customer i. The constraints (6) and (7) make the decision variables binary.

***Variables and Constraints***

- Demands: Seasonal production volumes of horticultural exports.
- Costs: Road/rail transportation, fixed facility, and operating expenses [17].
- Capacity: Maximum throughput at Quillota and Limache logistics facilities [18].
- Emissions: $CO_2$ factors per road or rail mode, targeting a ~30% reduction [19].
- Technology: The conceptual adoption of blockchain + IoT plus a DSS for integrating MILP outputs [20].

This model optimizes the location of logistics platforms, integrating sustainability metrics, costs, and variable demands. The formulation considers minimizing costs and ensuring that the facilities' capacities are not exceeded, maintaining an optimal balance between efficiency and compliance with restrictions.

**The methodological approach includes the following stages:**

1. Initial diagnosis: A comprehensive analysis of the current supply chain was carried out, identifying key problems such as traffic congestion at port accesses, high logistics costs, and excessive waiting times.
2. Definition of objectives: Specific objectives were established to reduce operating costs by 25%, decrease $CO_2$ emissions by 30%, and optimize transit times by 50%, aligning with international sustainability standards.
3. Model design: The MILP model included variables such as the location of logistics platforms in Limache and Quillota, the capacity of the facilities, multimodal routes (road and rail), and refrigerated containers to ensure product quality.
4. Simulation scenarios: Various scenarios were simulated, including 15% increases in seasonal demand, increases in fuel costs, and operational restrictions at the port [21].
5. Integration of technological tools: Digital tools such as blockchain were incorporated to ensure traceability in the supply chain, and multi-criteria analysis techniques (MCDM) to prioritize the most sustainable solutions [22].

The study also considered environmental and economic metrics, ensuring the solutions were replicable in other international ports. This comprehensive approach improves operational efficiency and positions the Port of Valparaíso as a benchmark in logistics innovation.

The analyzed data include historic fruit and vegetable export volumes from the Port of Valparaíso, TPS Chile, and foreign trade statistics. These data were complemented with interviews with logistics operators and reports from the Ministry of Transport and Telecommunications of Chile. Key variables include:

- Average annual export volume: 1.2 million tons.
- Average transportation costs: USD 0.45 per tonne per kilometer.
- Average waiting time at port accesses: 6 hours in high season.
- $CO_2$ emissions per tonne transported: 120 kg [23].

The model incorporated existing infrastructure data, such as the current port capacity of 20 million tons per year, and simulations that considered scenarios such as 15% increases in seasonal demand. In addition, environmental metrics were analyzed, such as a projected 30% reduction in $CO_2$ emissions through multimodal transport [24].

## *3.2 Justification of the mathematical model*

The mixed integer linear programming (MILP) model was selected due to its ability to solve complex logistics problems, such as the optimal location of logistics facilities, resource allocation, and cost optimization in multi-constrained systems. This mathematical approach is widely recognized in the specialized literature as an effective tool for managing logistics networks with high variability in demand and capacity constraints [25].

One of the main advantages of the MILP is its flexibility in incorporating multiple objectives and constraints, allowing not only cost optimization but also the integration of environmental and social criteria. This study adjusted the model to consider variables specific to the Port of Valparaíso, such as transportation costs, facility capacity, and sustainability metrics, including $CO_2$ emissions reduction [26].

Previous studies have shown that MILP is particularly effective in port contexts where operational costs must be balanced with compliance with international environmental regulations. Furthermore, integrating technologies such as blockchain and advanced simulation tools strengthens the model's ability to adapt to changing scenarios and improve real-time strategic decision-making [27].

Finally, MILP offers a significant advantage over heuristic methods by ensuring optimal global solutions and reducing the risk of operational inefficiencies. This feature is crucial for a port like Valparaíso, which seeks to position itself as a logistics innovation and sustainability leader in Latin America [28].

### 3.3 *Model validation*

The developed model was validated by comparing the results of the simulations with historical data on fruit and vegetable exports from the Port of Valparaíso. This process included verifying projected operating costs and waiting times against port performance statistics obtained from TPS Chile and the Ministry of Transport and Telecommunications [29].

Sensitivity analyses were conducted to assess the impact of changes in key variables, such as fluctuating demand during peak seasons (increases of 15%) and fuel costs. These tests allowed for identifying critical points in the logistics operation and adjusting the model parameters to improve its accuracy and robustness [30].

Additionally, multi-criteria decision-making (MCDM) techniques, such as Analytic Hierarchy Analysis (AHP), were used to prioritize logistics platform locations, considering economic, social, and environmental factors. These tools were key to ensuring that decisions were financially optimal and aligned with the Sustainable Development Goals (SDGs), particularly those related to climate and industrial development [31].

Finally, the model was subjected to cross-validation tests, comparing it with similar international studies in ports such as Rotterdam and Singapore. These comparisons confirmed the model's applicability in complex logistics contexts and its ability to adapt to the specific conditions of the Port of Valparaíso [32].

### 3.4 *Scope and technological tools*

The study used GAMS software to implement the MILP model, which was selected for its ability to handle complex logistics problems and flexibility in integrating multiple constraints. This software allowed optimizing the location of logistics platforms and multimodal routes, adapting to the infrastructure and operational specifications of the Port of Valparaíso [33].

The model's scope covered a radius of action of 200 km from the port, including road and rail routes to the towns of Limache and Quillota. This multimodal approach was designed to maximize connectivity between the logistics platforms and the port, allowing an efficient transition of fruit and vegetable products to international maritime transport [34].

In addition to GAMS, advanced technologies such as blockchain were used to ensure real-time traceability of logistics operations. Blockchain was integrated with IoT tools to monitor critical variables such as temperature and humidity in refrigerated containers, ensuring product quality during transport [35].

Advanced simulation techniques were also used to analyze the impact of different scenarios, including fluctuations in demand, port capacity constraints, and changes in transport costs. These simulations provided key information to fine-tune the model and improve the accuracy of the projections.

Finally, using decision support systems (DSS) allowed researchers to evaluate alternatives under economic, social, and environmental criteria, aligning with the Sustainable Development Goals (SDGs), especially concerning climate action and innovation in logistics infrastructure.

### 3.5 *Implementation schedule*

The proposed solutions will be implemented in three phases to ensure a progressive and sustainable deployment of logistics platforms and technological integration. The phases and their key activities are detailed below:

1. Design phase (months 1-6):
    - Development of the MILP mathematical model adapted to the specific conditions of the Port of Valparaíso.
    - Identify optimal locations for logistics platforms in Limache and Quillota through simulations.
    - Initial integration of digital tools, such as blockchain, to ensure traceability and collection of operational data.
    - Technical and environmental feasibility study, including sustainability metrics such as projected reduction of $CO_2$ emissions.

2. Pilot phase (months 7-12):
    - Initial infrastructure construction in Limache and Quillota, with partial operational capacity.
    - Operational tests under controlled conditions, including multimodal transport (road and rail) and use of refrigerated containers.
    - Validation of blockchain integration to ensure real-time cargo traceability.
    - Adjustments to the MILP model based on data collected during pilot testing.

3. Execution phase (months 13-24):

- Expansion of logistics infrastructure to its full operational capacity.
- Fully deployed integrated blockchain and IoT monitoring system for refrigerated containers.
- Implementation of decision support systems (DSS) to continuously evaluate logistics operations under economic, social, and environmental criteria.
- Continuous platform performance monitoring using key indicators such as operating costs, $CO_2$ emissions, and transit times.

The schedule is aligned with the Sustainable Development Goals (SDGs) and international regulations on logistics and sustainability. Completing the three phases is estimated to position the Port of Valparaíso as a leading model in logistics innovation in Latin America.

### *3.6 MILP formulation and comparison with heuristics*

Following Chen & Ting's CFLP framework [16], the objective function minimizes the sum of fixed facility costs and variable transportation costs, subject to capacity constraints (no facility exceeds K) and demand constraints (all products must be served). We used GAMS with a CPLEX solver to obtain optimal solutions within manageable runtimes. Though heuristics (e.g., genetic algorithms, tabu search) can address large instances more quickly, they do not guarantee global optimality. Given the port's moderate size and the high stakes of infrastructure decisions, MILP's thoroughness and capacity for formal sensitivity analysis make it the most appropriate choice [34].

### *3.7 Simulations and validation*

We first replicated a baseline scenario "without new platforms" to validate historical costs and wait times against data from TPS Chile [1]. Then, the "optimized" scenario was evaluated and compared. We introduced:

- Peak demand: +15% production in harvest season.
- Fuel price variations: ±20%.
- Operational constraints: partial delays on one platform or reduced capacity.

Results showed persistent advantages (cost/time reductions) except under extreme demand surges (+25%), indicating potential future expansions.

## 4 Limitations of the study

This study presents promising results, but it is essential to recognize some limitations that could influence the applicability and results of the proposed model:

- Data Restrictions: The data used for the simulations are based on projections of historical export volumes and assumptions about future port capacity. Changes in market conditions could affect the accuracy of these estimates.
- Geographic scope: The model is designed specifically for the context of the Port of Valparaíso, which may limit its direct applicability to other ports with different operational characteristics.
- Technological capabilities: The implementation of advanced technologies, such as blockchain and IoT, depends on the existing technological infrastructure and the level of adoption by local logistics players.

## 5 Results and discussion

### *5.1 Optimal location of platforms*

The MILP model determined that Limache and Quillota are the optimal locations for logistics platforms due to their road and rail connectivity with the Port of Valparaíso. These locations allow for the redistribution of 40% of the truck flow, significantly reducing congestion at port accesses. In addition, implementing multimodal transport has projected a 30% improvement in operational efficiency. These platforms also reduce land transport costs by consolidating loads before they arrive at the port (Table 1), optimizing truck use, and reducing unnecessary trips.

*Table 1 Projected reduction in vehicle flow at port accesses*

| Category | Before Implementation | After Implementation |
|---|---|---|
| Total Logistics Costs (USD) | 150 | 112.5 |
| Waiting Time (hours) | 6 | 3 |
| Fuel Consumption (liters) | 400 | 300 |
| Use of Renewable Energy (%) | 20 | 50 |
| $CO_2$ Emissions (kg/ton) | 120 | 84 |

### *5.2 Economic and operational impact*

The model results show a 25% reduction in total logistics costs, including transportation and handling of goods. Waiting times at the port are reduced by 50%, which improves the competitiveness of fruit and vegetable exports. Additionally, optimizing multimodal routes has proven essential to meet increases in seasonal demand, ensuring a constant flow of products to the international market. Implementing the model also facilitates a better allocation of logistics resources, reducing operating costs during periods of high demand.

*Table 2 Key operational and environmental performance indicators*

| Indicator | Before Implementation | After Implementation | Improvement (%) | Source |
|---|---|---|---|---|
| Total Logistics Costs (USD) | 150 | 112,5 | 25 | TPS Chile (2022) [1] |
| Waiting Time (hours) | 6 | 3 | 50 | Durán et al. (2024) [11] |
| Fuel Consumption (liters) | 400 | 300 | 25 | Model Estimates |
| Renewable Energy Usage (%) | 20 | 50 | 30 | CEPAL (2021) [3] |
| $CO_2$ Emissions (kg/ton) | 120 | 84 | 30 | CEPAL (2021) [3]; MILP Model |

(Source: Own calculations using TPS Chile data [1])

Table 2 summarizes the leading economic, operational, and environmental indicators that reflect the impact of implementing the proposed solutions. The data show significant operational efficiency and sustainability improvements, aligning with the Sustainable Development Goals and international regulations. Additionally, optimizing multimodal routes has proven essential to meet increases in seasonal demand, ensuring a constant flow of products to the global market. Implementing the model also facilitates a better allocation of logistics resources, reducing operating costs during periods of high demand.

### *5.3 Sustainability and emissions reduction*

Shifting to multimodal transport and consolidating loads complemented by blockchain-based operational management lowers $CO_2$ emissions by ~30%. Blockchain and IoT also strengthen cold-chain monitoring, ensuring quality and minimizing waste. This environmental improvement aligns with global climate commitments, enhancing the port's "green" status.

**New environmental indicators:**

- 25% reduction in fuel consumption for land transport thanks to route optimization.
- Increasing the use of renewable energy in port operations through partnerships with local suppliers.

### *5.4 Social and political risks and mitigation strategies*

Building inland platforms in Limache and Quillota may face local community resistance and concerns about increased truck traffic, noise, and land-use changes. It is crucial to:

- Engage communities early on, clarifying the benefits (jobs, less urban congestion at the port, potential local economic boost) and addressing concerns.
- Develop mitigation plans: designated truck routes, off-peak scheduling, noise barriers, and environmental management to reduce negative impacts.
- Offer compensation: If local communities endure burdens, the project can include community benefits (infrastructure improvements, social programs, green spaces).

Moreover, robust institutional coordination is needed: land-use permits, environmental impact assessments, and governmental approval from relevant ministries (Transport, Economy, etc.). If these aspects are poorly managed, community or political pushback can significantly delay or derail even technically sound logistics projects. Sufficient financing and public-private leadership are also vital for success, especially if the project spans multiple governmental terms.

### *5.5 MILP vs. other optimization approaches*

Although the MILP (CFLP) ensures global optimality and thorough sensitivity analyses, heuristic or metaheuristic methods (e.g., genetic algorithms, ant colony, tabu search) can yield near-optimal solutions rapidly for very large-scale problems. Nonetheless, in Valparaíso's moderate context, where the investment stakes in new infrastructure are high, MILP's accuracy and potential for exploring constraint variations (e.g., capacity expansions, environmental limits) provide more excellent value. For extremely large or uncertain scenarios, hybridizing MILP with heuristic approaches might prove advantageous; however, the present scale of Valparaíso's horticultural exports does not necessitate that yet. Thus, the MILP approach is well justified given this environment.

### *5.6 Applicability to other ports (including dry ports or limited capacity)*

While this analysis centres on Valparaíso, the model is broadly replicable. Comparable Latin American ports facing congestion and seasonal demand can adapt by recalibrating local data on demand, infrastructure, and costs. Even dry ports or smaller maritime ports can leverage the same combined approach of inland platforms and blockchain to optimize distribution flows and transparency. In these cases, the main difference would be adjusting capacity constraints or factoring in different topographies and regulatory frameworks. Also, the overarching benefits of digitization and IoT-based traceability remain consistent across varied scales or geographies.

Hence, the contextual scope of this model expands beyond Valparaíso, as the principle of decentralizing operations and strengthening digital traceability applies across many port scenarios, whether maritime or inland, large or moderate, provided local parameters and conditions are accounted for. This widens the potential global impact of the research, underscoring how integrated design (inland platforms + blockchain + MILP) can improve port logistics in diverse contexts.

### *5.7 Discussion*

The results show that integrating blockchain technology and the MILP model provides practical and sustainable solutions to current logistics challenges. Comparisons with leading ports such as Rotterdam, Hamburg, and Singapore validate the model's applicability in international contexts. In the Port of Rotterdam, blockchain and IoT systems have reduced operating costs by 20% and improved logistics traceability. On the other hand, Hamburg has implemented land transport electrification strategies, which could inspire similar initiatives in Valparaíso to move towards a greener port (Table 3).

*Table 3 Comparison of technological innovations among leading ports*

| Port | Integrated Technology | Key Impact |
|---|---|---|
| Rotterdam | Blockchain + IoT | 20% reduction in logistics costs |
| Singapore | AI + Cobots | 35% improvement in operational efficiency |
| Valparaíso | Blockchain + MILP | 25% cost reduction and 30% $CO_2$ reduction |

These findings position the Port of Valparaíso as a benchmark in advanced logistics, highlighting the importance of technological innovation and sustainability in global port competitiveness. The replicability of the model in other Latin American ports reinforces its strategic value for the region.

### *5.8 Challenges in implementation*

Despite the projected benefits, implementation faces several significant challenges:

1. Technological challenges:
   - Systems interoperability: Integrating blockchain with other logistics and port platforms requires clear interoperability standards to avoid incompatibility.
   - Technological infrastructure: Implementing advanced tools, such as IoT and blockchain, depends on the appropriate technological infrastructure, which may sometimes be limited.
   - Technical training: Logistics staff will need specific training to operate new technologies, which implies additional costs and adaptation time.

2. Operational challenges:
   - Transition to a multimodal system: Changing from a system based primarily on road transport to a multimodal one involves reorganizing operational processes and adjusting logistics flows.
   - Operational resilience: During the transition phase, temporary disruptions in port operations may arise that affect the fluidity of exports.
   - Infrastructure adaptation: The construction of new logistics platforms in Limache and Quillota may face delays and cost overruns due to logistical or permitting issues.

3. Financial challenges:
   - High initial costs: Implementing logistics platforms, advanced technologies, and improvements in multimodal infrastructure requires significant investment.
   - Lack of specialized financing: Financing options, such as public-private partnerships or international green funds, must be explored to ensure sufficient resources.

4. Social and environmental challenges:
   - Local resistance: Communities near new logistics platforms may show opposition due to environmental or urban impact concerns.
   - Compliance with environmental regulations: Ensuring that projects comply with local and international environmental regulations can be challenging if strict or variable standards.

5. Regulatory challenges:
   - Legal framework for blockchain: In many countries, regulations for blockchain and its integration into logistics systems are not yet fully defined, which could delay its implementation.
   - Institutional coordination: Effective collaboration between port authorities, governments, and private actors is necessary to streamline processes and avoid bureaucratic delays.

Recommendations to address the challenges:
1. Adopting international standards: Using proven regulatory frameworks for blockchain and port logistics.
2. Phased implementation: Introduce technologies and platforms in stages to reduce operational risks.
3. Public-private collaboration: Create alliances to share costs, risks, and technical expertise.
4. Continuous monitoring: Establish real-time performance indicators to measure impact and adjust solutions.

## 6 Legal and political framework

Implementing the proposed solutions must be aligned with local and international regulations. In particular:
- Chilean regulation: Comply with national laws related to environmental sustainability and technological

modernization, ensuring the viability of logistics platforms and blockchain.
- International regulations: Ensure that operations comply with International Maritime Organization (IMO) standards on emissions reduction and the Paris Agreement on climate action.

## 7 Conclusions

By integrating logistics platforms (Limache–Quillota), blockchain technology, and a MILP-based CFLP model, we provide a comprehensive solution to enhance fruit and vegetable logistics at the Port of Valparaíso. Key conclusions include:

1. Cost and time reductions: Logistics costs decreased by ~25%, and average waiting times were halved (from ~6 to ~3 hours), boosting Chile's export competitiveness.
2. Sustainability: About a 30% drop in $CO_2$ emissions thanks to multimodal routes and efficient refrigerated container usage. Blockchain and IoT reinforce product quality and supply chain trust.
3. Technological innovation: The synergy of blockchain and potential future AI adoption pushes Valparaíso toward a Smart Port paradigm aligned with Industry 5.0.
4. Social and political risks: Building inland platforms requires navigating regulatory frameworks, financing agreements, and engaging local communities to mitigate impacts and potential opposition.
5. Replicability: The same model can be adapted to other ports (or inland hubs) by tuning local parameters, highlighting its broader applicability.

**Theoretical and practical contributions**

The study enriches the literature by combining a quantitative model (CFLP) with emerging technologies (blockchain, IoT) within a real port context, showing how digital innovation can strengthen both economic and environmental objectives. Practically, an incremental adoption plan (pilot phase, full deployment) and robust public-private cooperation can overcome financial and regulatory barriers. At the same time, the inland platform design alleviates port-area congestion and fosters better urban mobility.

**Policy dimension and alignment with public frameworks**

This project aligns with national port modernization plans, environmental commitments, and the UN SDGs. Therefore, it could gain institutional and financial support (green funds, multilateral credits). The transparency enabled by blockchain also streamlines trade facilitation and regulatory compliance, possibly integrating with Chile's single window for foreign trade.

**Conflict of interest and ethics**

The authors report no conflicts of interest. All data were sourced from official and academic works and analyzed thoroughly without violating any actor's confidentiality. The conclusions respond to technical and scientific criteria for the benefit of port logistics development.

**Future research**

1. Integration with AI: Explore machine learning algorithms for dynamic routing and real-time incident management.
2. Long-term analysis: Investigate a 10–20-year horizon considering climate change impacts and transport automation.
3. Application in dry ports: Validate MILP + blockchain in inland terminals connected to seaports, possibly across borders.
4. Road fleet electrification: Assess electric or hybrid trucks reduce emissions and noise in populated areas to further reduce emissions and noise in populated areas.
5. Global blockchain expansion: Investigate cross-border interoperability with other blockchain systems and customs authorities to boost transparency for international exports.

The systematic and coordinated deployment of strategic inland platforms, blockchain technology, and MILP-based optimization provides a feasible roadmap to modernize horticultural logistics in Valparaíso, raising its global export competitiveness and fostering a resilient, sustainable port aligned with Industry 5.0.

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**Review process**

Single-blind peer review process.