Multi-Echelon Distribution Network Optimization in Multi-Product Food Supply Chains Using Mixed Integer Linear Programming

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**Abstract.** The distribution of ice cream presents inherent complexities in managing delivery flows and maintaining product availability across the distribution network. Ice cream distributors are required to ensure consistent stock levels at all distribution facilities. This study aims to optimize the company’s multi-echelon distribution network by introducing additional facilities such as distribution centers (DCs). The proposed approach employs a Mixed Integer Linear Programming (MILP) method to minimize total distribution costs. The MILP model integrates shipment decisions from manufacturing plants to DCs and from DCs to retailers, while also determining the activation of DC facilities based on minimum operating costs. A case study implementation revealed that the proposed optimization reduces the company’s distribution cost by 19.09% compared to its initial operational cost. The result network configuration incorporates two additional DCs, which facilitate product consolidation and retailer allocation based on geographical proximity and cost efficiency. The inclusion of DCs significantly lowers logistics operating expenses, improves coordination in meeting retailer demand, and enhances delivery speed. Furthermore, the multi-echelon strategy contributes to more effective and efficient inventory management throughout the supply chain.

**Keywords:** Distribution, Multi Echelon, Food Supply Chain, Mixed Integer Linear Programming

# INTRODUCTION

Perishable products such as ice cream require strict temperature control throughout the supply chain. Even brief deviations from the optimal storage temperature of −18 °C can cause partial melting, crystal growth, and textural damage. These changes lead to a significant reduction in product quality and shelf life [1]. Unlike non-perishable goods, frozen dairy products are still vulnerable during transportation, especially over long distances or when cold chain capacity is limited. Under such conditions, poor temperature control can cause major economic losses and lower consumer satisfaction [2]. In many supply chains, particularly in developing regions, cold chain logistics infrastructure is still underdeveloped [3]. A lack of refrigerated transport and limited intermediate storage facilities often result in longer transit times, which increase the risk of temperature abuse [4]. Ice cream is especially sensitive to thermal fluctuations and can experience irreversible quality deterioration once partial melting occurs. The deterioration affects not only sensory attributes but also food safety [5].

One effective approach to reducing these risks is the introduction of distribution centers (DCs) equipped with frozen storage capabilities into the distribution network. DCs act as intermediate nodes between production facilities and retail outlets, enabling bulk shipments to be broken down into smaller, more frequent deliveries [6]. The DCs shortens the final delivery distance and reduces the time products spend in transit, thereby minimizing exposure to temperature deviations [7]. When strategically located, DCs can significantly improve cold chain reliability and service levels [8]. The addition of a DC transforms a single-echelon distribution system into a multi-echelon network. Multi-echelon systems allow greater flexibility in inventory allocation, transportation planning, and service responsiveness [9]. For perishable products, this flexibility helps reduce spoilage, improve stock availability, and maintain more stable product quality when the goods reach retail points.

Mixed Integer Linear Programming (MILP) can be used to determine the optimal location and operational role of a distribution center (DC) by modeling the network design problem. This approach is widely applied in supply chain network design because it can address multiple objectives, such as minimizing total cost while meeting service constraints [10]. In practice, however, cold chain operations face uncertainties in demand, lead times, and transportation conditions. These factors are difficult to capture in static optimization models. Previous literature provides multiple examples of multi-echelon and MILP applications in perishable and cold-chain contexts. For instance, two-echelon inventory-routing formulations and multi-period multi-echelon perishable models have been developed to explicitly account for decay, shelf life, and temperature-dependent loss, showing benefits of intermediate depots or hubs in reducing deterioration and distribution costs [11]. Studies focusing on cold-chain DC location and design also highlight trade-offs between facility operating costs, transport cost reductions, and improvements in product quality and service [12]. Specific works have even modelled distribution problems for frozen goods such as ice cream to capture time-sensitive quality loss and operational constraints [13].

This study proposes the development of a hybrid MILP for optimizing a multi-echelon distribution network for ice cream products. The primary aim is to evaluate the benefits of introducing a frozen storage distribution center to reduce product losses caused by melting during transportation. The proposed framework combines strategic network design with adaptive operational control, offering a practical solution to enhance cold chain resilience and product quality preservation.

# RESEARCH METHODOLOGY

This study addresses the distribution network optimization problem for a frozen dessert manufacturer, specifically focusing on ice cream. Ice cream is a highly perishable and temperature-sensitive product. In the current single-echelon system, products are transported directly from the manufacturing plant to retailers. Prolonged transit times in non-optimal conditions cause partial or complete melting, leading to significant product losses and increased costs.To address this issue, we propose the addition of a refrigerated distribution center (DC) to create a multi-echelon network. The DC serves as an intermediate storage and consolidation point, reducing direct shipment distances to retailers, improving temperature control, and minimizing product melt losses. This study applies the Mixed Integer Linear Programming (MILP) method to develop an optimized multi-echelon distribution network model, adapted from the framework of Uyar [14].The MILP approach is chosen for its ability to handle combinatorial decision-making problems, including the activation of distribution centers (DCs), the assignment of customers to facilities, and the optimization of product flows.

|  |  |
| --- | --- |
| **Notation** | |
|  |  |
|  | : Manufacturing plant |
|  | : Distribution center (DC) |
|  | : Retailer |
|  | Demand of product at retailer (tons) |
|  | : Production capacity of product at plant (tons) |
|  | : Transportation cost per ton for shipping product *i* from plant to DC |
|  | : ransportation cost per ton for shipping product *i* from DC to retailer |
|  | : Fixed cost for operating DC |
|  |  |
| **Decision Variables** | |
|  | : Quantity (tons) of product shipped from plant to DC |
|  | : Binary variable indicating whether retailer is served by DC |
|  | : Binary variable indicating whether DC activated |

**Objective Function**

|  |  |
| --- | --- |
|  | (1) |
| **Constraint** |  |
|  | (2) |
|  | (3) |
|  | (4) |
|  | (5) |
|  | (6) |
|  | (7) |

The objective function (1) of this model aims to minimize the total distribution cost, which comprises the transportation cost from manufacturing plants to distribution centers (DCs), the transportation cost from DCs to retailers, the fixed cost of opening DCs, and the costs associated with product consolidation and deconsolidation at DCs. The model is subject to five main constraints. Constraint (2) ensures that the production capacity of each plant does not exceed its maximum allowable limit. Constraint (3) enforces product flow balance at each DC, ensuring that the total quantity received matches the aggregate demand of the retailers it serves. Each retailer must be exclusively served by a single DC, as defined by Constraint (4). Constraint (5) guarantees that a DC can only serve retailers if it is activated, linking the allocation and activation binary variables. Finally, Constraint (6) enforces the binary nature of the decision variables for retailer assignment and DC activation, ensuring operational feasibility and decision accuracy.

# RESULT AND DISCUSSION

The proposed MILP model was implemented using the given network configuration, product demand, plant capacities, transportation costs, and fixed operating costs for distribution centers (DCs). The optimization was performed using LINGO software version 18. The case study was conducted for an ice cream manufacturing company operating with 17 retail outlets distributed across its service area. The initial company’s total distribution cost was IDR 8,623,240, which included transportation costs from plants to retailers and other related operational expenses in a single-echelon distribution setup. The results of the proposed model indicate an optimal multi-echelon distribution configuration that significantly reduces total distribution costs, ensures balanced product flows across facilities, and fully satisfies retailer demand while minimizing the risk of product loss due to melting during transport.

**Table 1.** Fixed Cost at DC

|  |  |
| --- | --- |
| DC | Fixed Cost (IDR) |
| DC1 | 50,500 |
| DC2 | 71,800 |

**Table 2.** Plant Capacity Data

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Product | Plant Capacity | | Transportation cost (IDR) | | | |
| Plant 1 (Pc1) | Plant 2 (Pc2) | P1/ DC1 | P1/ DC2 | P2/ DC1 | P2/  DC2 |
| Gelato (IC1) | 3000 | 4000 | 112 | 122 | 100 | 112 |
| Sorbet (IC2) | 2500 | 4500 | 131 | 121 | 105 | 120 |
| Frozen Yogurt (IC3) | 2000 | 5000 | 144 | 132 | 120 | 132 |
| Soft Serve (IC4) | 3500 | 3500 | 173 | 141 | 117 | 135 |
| Sherbet (IC5) | 2000 | 5000 | 167 | 132 | 120 | 140 |
| Rolled Ice Cream (IC6) | 3500 | 4000 | 168 | 153 | 128 | 122 |

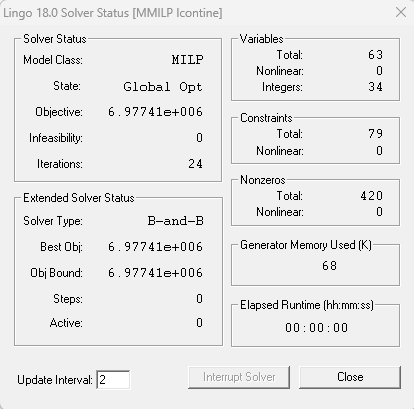
Table 1 presents the fixed operating costs for the two candidate distribution centers (DCs). DC1 incurs a fixed cost of IDR 50,500, while DC2 requires a higher fixed cost of IDR 71,800. Although the operating expense for DC2 is greater, the optimization results indicate that activating both DCs yields a more cost-efficient distribution network overall. As shown in Table 2, plant capacities vary by product type, with Plant 2 generally having a larger production capacity than Plant 1, except for Soft Serve (IC4) and Rolled Ice Cream (IC6), where capacities are equal or higher in Plant 1. Transportation costs from plants to DCs also vary across products and routes. For example, shipping Gelato (IC1) from Plant 1 to DC1 costs IDR 112 per ton, whereas sending it to DC2 costs IDR 122 per ton. These differences directly influence routing decisions, as the model prioritizes lower-cost shipment routes, when possible, while still considering capacity and demand constraints.

**Table 3.** Proposed product shipment from plants to DCs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Product | Plant 1 | | Plant 2 | |
| DC1 | DC2 | DC1 | DC2 |
| Gelato (IC1) | 1560 | 1440 | 0 | 2135 |
| Sorbet (IC2) | 1135 | 0 | 0 | 2555 |
| Frozen Yogurt (IC3) | 0 | 2000 | 1428 | 580 |
| Soft Serve (IC4) | 0 | 2535 | 930 | 0 |
| Sherbet (IC5) | 785 | 1215 | 0 | 1120 |
| Rolled Ice Cream (IC6) | 1370 | 0 | 0 | 3025 |

The optimized allocation of product shipments from plants to distribution centers (DCs) in Table 3 reflects the strategic balance between minimizing transportation costs and meeting capacity and demand constraints. For example, Gelato (IC1) is partially supplied from Plant 1 to both DC1 and DC2 (1,560 and 1,440 tons, respectively) while the remainder is sourced from Plant 2 exclusively to DC2 (2,135 tons). This allocation leverages the proximity and cost advantages of Plant 1 for DC1 while utilizing Plant 2’s higher capacity for meeting DC2’s demand. Certain products are routed predominantly from a single plant to a specific DC, indicating cost-driven specialization. Sorbet (IC2), for instance, is shipped from Plant 1 only to DC1 and from Plant 2 solely to DC2, eliminating cross-routing and thus reducing handling complexity. Similarly, Rolled Ice Cream (IC6) is supplied from Plant 1 to DC1 and from Plant 2 to DC2 without intermixing, which likely reduces operational handling time and risk of quality degradation for these perishable items. In some cases, products are split between plants and DCs to balance load and fulfill demand efficiently. Frozen Yogurt (IC3) demonstrates this pattern, with shipments from Plant 1 directed entirely to DC2 (2,000 tons) while Plant 2 supplies both DC1 (1,428 tons) and DC2 (580 tons).

The results are consistent with prior research on multi-echelon distribution optimization using MILP. For instance, Rohaninejad, et al. [15] highlight that optimal allocation in a multi-echelon supply chain often results in partial specialization of facilities, with selective cross-routing only when cost and capacity constraints justify it. Similarly, Orjuela-Castro, et al. [16] note that in perishable product supply chains, minimizing transit time is as critical as minimizing cost, and a carefully balanced flow between sources and intermediaries can significantly reduce spoilage.



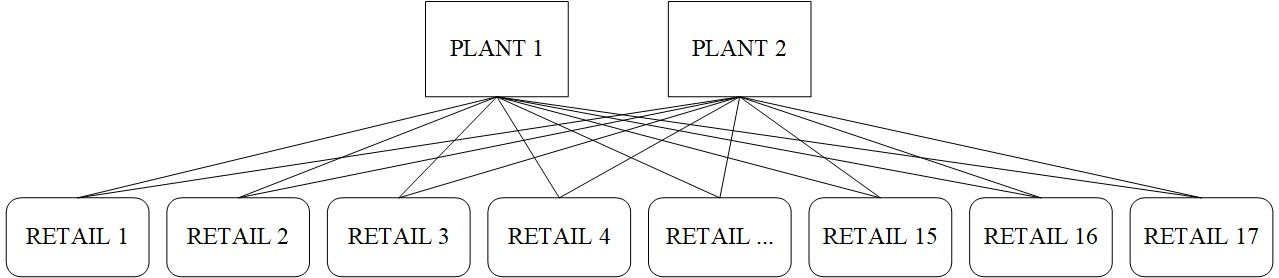
**Figure 1**. Lingo result of MILP

**Table 4. Proposed shipments from DCs to retailers**

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Retail | DC 1 | | | | | | DC 2 | | | | | |
| IC1 | IC2 | IC3 | IC4 | IC5 | IC6 | IC1 | IC2 | IC3 | IC4 | IC5 | IC6 |
| Retailer 1 | 174 | 221 | 194 | 245 | 174 | 137 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retailer 2 | 139 | 181 | 250 | 164 | 133 | 148 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retailer 3 | 0 | 0 | 0 | 0 | 0 | 0 | 210 | 226 | 176 | 185 | 204 | 130 |
| Retailer 4 | 224 | 157 | 106 | 189 | 187 | 206 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retailer 5 | 166 | 206 | 153 | 130 | 131 | 116 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retailer 6 | 0 | 0 | 0 | 0 | 0 | 0 | 157 | 144 | 124 | 127 | 179 | 131 |
| Retailer 7 | 0 | 0 | 0 | 0 | 0 | 0 | 152 | 208 | 242 | 129 | 202 | 147 |
| Retailer 8 | 100 | 124 | 196 | 102 | 151 | 107 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retailer 9 | 208 | 183 | 220 | 147 | 196 | 121 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retailer 10 | 0 | 0 | 0 | 0 | 0 | 0 | 119 | 169 | 156 | 227 | 124 | 195 |
| Retailer 11 | 148 | 221 | 215 | 132 | 162 | 147 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retailer 12 | 102 | 166 | 177 | 163 | 206 | 164 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retailer 13 | 197 | 220 | 163 | 144 | 135 | 137 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retailer 14 | 0 | 0 | 0 | 0 | 0 | 0 | 186 | 124 | 135 | 138 | 126 | 196 |
| Retailer 15 | 169 | 146 | 107 | 184 | 174 | 161 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retailer 16 | 171 | 134 | 185 | 103 | 143 | 172 | 0 | 0 | 0 | 0 | 0 | 0 |
| Retailer 17 | 224 | 197 | 150 | 139 | 175 | 147 | 0 | 0 | 0 | 0 | 0 | 0 |

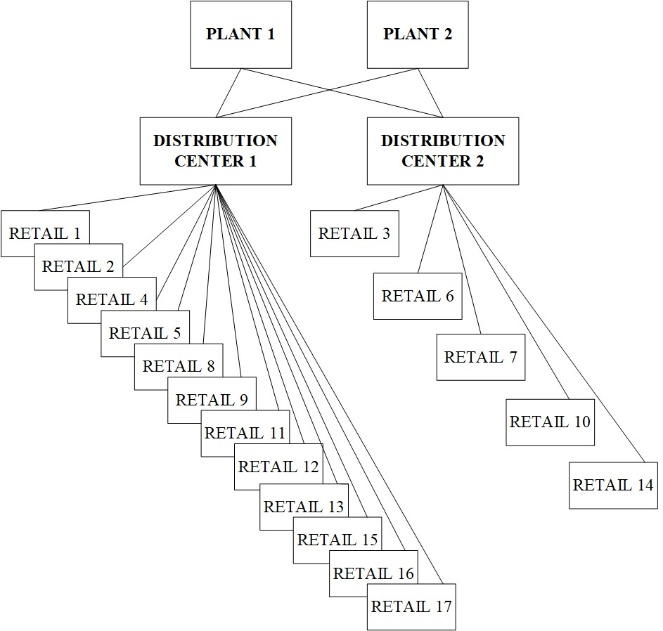
The shipment allocation in Table 4 reveals a clear clustering strategy in which each retailer is served exclusively by a single distribution center (DC). Retailers R1, R2, R4, R5, R8, R9, R11–R13, R15, R16, and R17 are fully supplied from DC1, while R3, R6, R7, R10, and R14 are supplied entirely from DC2. This allocation pattern is consistent with the single-sourcing principle in multi-echelon distribution design, which minimizes complexity in scheduling, reduces administrative overhead, and ensures product traceability [17]. The assignment also reflects geographical proximity optimization which is DC1 primarily serves retailers likely located closer to its facility, reducing transportation lead time and energy costs.

Based on the multi-echelon distribution optimization results obtained from LINGO 18, as illustrated in Figure 1, the total distribution cost can be reduced to IDR 6,977,410. By adding two distribution centers (DCs), the overall distribution cost decreased from IDR 8,623,240 in the previous single-echelon configuration to IDR 6,977,410, resulting in a cost saving of approximately 19.09%. This optimization outcome reinforces the fundamental concepts of supply chain management theory, particularly the multi-echelon distribution approach, which emphasizes the strategic role of intermediary facilities such as DCs in reducing the average delivery distance per unit, lowering transportation costs, and facilitating better control over product flows [18, 19].



**Figure 2.** Initial distribution network

Figure 2 illustrates the company’s initial single-echelon distribution system, in which products are delivered directly from manufacturing plants to retailers without any intermediary facility. This strategy leads to higher transportation costs, as each shipment from the plant to a retailer must be made separately, eliminating opportunities for load consolidation and resulting in inefficient routing. Additionally, the absence of intermediate cold storage facilities increases the risk of product losses due to ice cream melting during transportation. This aligns with classical supply chain theory, which states that without consolidation points such as distribution centers (DCs), transportation costs tend to be higher because economies of scale in shipments cannot be fully exploited [20]. Furthermore, Figure 3 presents the proposed distribution plan, which incorporates two DCs that consolidate products from plants before delivering them to retailers. This multi-echelon distribution model reduces the total travel distance, optimizes delivery routes, and directly lowers logistics costs while mitigating the risk of product quality degradation.



**Figure 3.** Proposed distribution network

# CONCLUSION

This study demonstrates that the addition of two distribution centers (DCs) within a multi-echelon distribution network is an effective strategy for reducing transportation costs in the ice cream supply chain. By implementing a redesigned distribution system in which products are consolidated at DCs before delivery to retailers, the total distribution cost was reduced from IDR 8,623,240 to IDR 6,977,410, representing a cost savings of 19.09%. The Mixed Integer Linear Programming (MILP) approach successfully leveraged location efficiency, reduced average travel distance, enhanced load consolidation, and minimized the risk of product melting due to prolonged transportation. These results highlight that strategically located DCs can serve as a practical means to lower transportation costs and improve supply chain performance. Therefore, it is recommended that the company adopt this multi-echelon distribution structure on a sustained basis, supported by advanced technologies to further enhance responsiveness and operational efficiency.

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