Otomatik Depolama Sistemi Yerleşim ve Çizelgeleme Eniyilemesi

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Arçelik Eskişehir Buzdolabı İşletmesi

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ÖZET

Arçelik Eskişehir Buzdolabı İşletmesi'nde kullanılan Otomatik Depolama ve Geri Alma Sistemi (AS/RS), operasyonel darboğazlara ve aşırı bekleme sürelerine neden olan tecrübeye dayalı sezgisel yöntemlerle işletilmektedir. Bu problemleri gidermek amacıyla, materyaller için depolama yeri atama ve vinç çizelgeleme süreçlerini eş zamanlı olarak optimize eden bir karar destek sistemi geliştirilmiştir. Çözüm kapsamında, malzeme devir hızlarına dayalı K-ortalamalar kümeleme yöntemi ve Karma Tam Sayılı Doğrusal Programlama (MILP) modelleri kullanılarak gerçek zamanlı karar verme sistemi oluşturulmuştur. Yapılan pilot çalışması sonucunda, sistemin iş çıkarma kapasitesi korunurken ortalama vinç seyahat mesafesinde %25 ve kuyrukta biriken işlerde %41 oranında azalma sağlanmıştır. Geliştirilen yazılım tabanlı çözüm, yıllık yaklaşık 807.600 kWh enerji tasarrufu ve operasyonel verimlilik artışı sağlamaktadır.

Anahtar Sözcükler: Otomatik Depolama ve Geri Alma Sistemi, Depolama Yeri Atama, Vinç Çizelgeleme, Lojistik Optimizasyonu.

Optimization of Storage and Crane Scheduling in Automated Storage System

Abstract

The Automated Storage and Retrieval System (AS/RS) at the Arçelik Eskişehir Refrigerator Plant operates using experience-driven heuristics which led to operational bottlenecks and excessive waiting times. To address these structural inefficiencies, a solution approach was developed to jointly optimize storage location assignment and crane sequencing. The proposed approach established a real-time decision-making system using turnover-based K-means clustering and Mixed-Integer Linear Programming (MILP) models. Pilot study demonstrates a 25% reduction in average crane travel distance and a 41% decrease in average queue depth. The solution achieves an estimated 807,600 kWh in annual energy savings alongside significant labor efficiency gains.

Keywords: Automated Storage and Retrieval System (AS/RS), Storage Location Assignment, Crane Sequencing, Logistics Optimization.

1 Company and System Analysis

1.1 Company Description

Beko is Europe's largest home appliances company and a global leader in the industry, operating in more than 55 countries with over 55,000 employees worldwide (Beko Corporate, 2025). As a global brand of Arçelik, Beko combines large-scale manufacturing capability with a strong focus on innovation, efficiency, and sustainability. The Eskişehir Refrigerator Plant, one of Beko's key production facilities, is recognized for its advanced digital infrastructure and Industry 4.0 practices (Home Appliances World, 2021).

1.2 Current System Analysis

The Beko Eskişehir Refrigerator Plant operates five production lines supported by an Automated Storage and Retrieval System (AS/RS), which handles approximately 65% of internal material flow. The system consists of 7 aisles with dedicated cranes and stores materials in Eurobox and half-Eurobox containers, which are transferred to production lines through conveyors, monoporters, and elevators. A representation of the AS/RS overview can be seen in Figure 1.

Although the AS/RS is a critical component of the production system, it currently operates based on experience-driven heuristics developed for significantly lower production volumes. While originally designed for around 500 units per shift, the system now supports over 4,500 units and handles more than 15,000 material types, and much higher throughput levels, creating a mismatch between system logic and operational requirements.

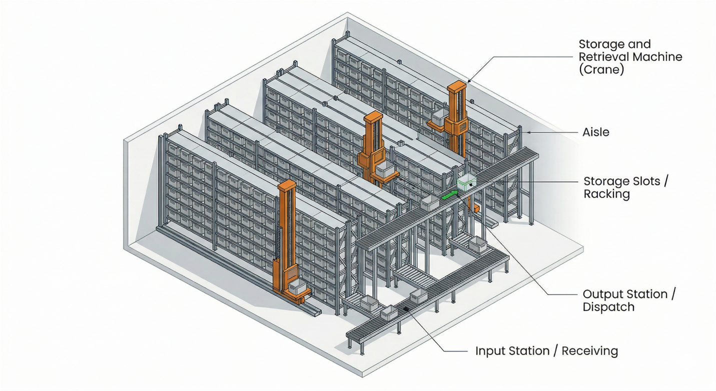


Figure 1: AS/RS Overview

2 Problem Definition

The AS/RS operates with an automated work-order system where material requests are generated based on workstation needs, and different box combinations can satisfy the same demand. The existing logic assigns cranes based on simple availability, while materials are placed in the first available slot regardless of demand frequency. Furthermore, retrieval tasks are executed chronologically rather than through optimized scheduling. While the workload is distributed across cranes, this process lacks a formal mathematical model and fails to ensure optimal decision-making. The heatmap in Figure 2 reveals a nearly uniform distribution of crane visits across the rack; while darker cells indicate higher activity, these high-frequency points are scattered rather than being optimized near the Input/Output (I/O) point to minimize travel distance. In addition, the system experiences fluctuating demand with peak load periods, during which current storage and retrieval policies lead to congestion and delays.

Under the current heuristic-based structure, this leads to inefficiencies in both storage assignment and crane scheduling , especially at high production levels. The proposed approach integrates data analysis, mathematical models, and algorithms to improve system responsiveness, balance crane workload, and reduce unnecessary movements. The scope is limited to optimizing product placement within the AS/RS and crane operations, excluding other material handling systems.

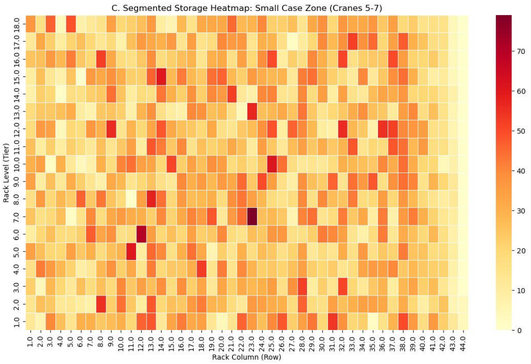


Figure 2: AS/RS Crane Visit Frequency Heatmap

3 Proposed Solution Strategy

3.1 Critical assumptions

The model is built under several simplifying assumptions. Each box is treated as an indivisible unit containing a single material stock code (MSC), and its contents cannot be modified. The AS/RS layout is fixed, including the number and locations of slots and dedicated cranes. Cranes travel at a constant speed, and travel times between slots are calculated using Chebyshev distance, reflecting simultaneous horizontal and vertical movement. Pickup and deposit times are 20 seconds each, and each input point on the single conveyor belt can hold only one box due to the absence of buffer space. Load orders cannot be reassigned between cranes, although they may be re-sequenced within the same queue, whereas unload orders may be reassigned if the item is available in another aisle. All primary material-handling equipment is assumed failure-free, and external supply chain disruptions, production delays, and downtime are excluded from the model.

3.2 Major constraints

The AS/RS system handles two box types, namely small and large boxes, whose storage slots are physically separated and therefore cannot be interchanged. Each crane can carry only one box per command cycle and can handle only a single box at a time. Cranes move only parallel to their assigned aisle, without lateral movement, but can serve storage slots on both the left and right sides of that aisle. In addition, each storage slot can hold at most one case at any given time, and every actively managed box must be assigned to exactly one slot within the system. Once a slot is reserved for a load task, it cannot be assigned to another task until the operation is completed or canceled. Finally, an unload task can only be executed if the target slot contains the requested MSC at the time of execution.

3.3 Objectives

The overall objective of the proposed solution strategy is to improve AS/RS operational efficiency by reducing work order completion times and balancing workload across aisles. In this way, the system aims to shorten storage and retrieval completion times, improve crane utilization, and increase the number of completed work orders within the existing system structure.

4 Solution Approach

4.1 Conceptual Model

The proposed solution adopts a layered control system that decomposes the AS/RS scheduling problem into interacting components (Yang et al., 2015). Aisles are modeled as parallel, independent servers, allowing the system to focus on workload balancing and minimizing travel time. The control logic is event-driven, with optimization triggered only by state changes, such as the arrival of new work orders, ensuring both computational efficiency and real-time responsiveness. The overall workflow is illustrated in Figure 3.

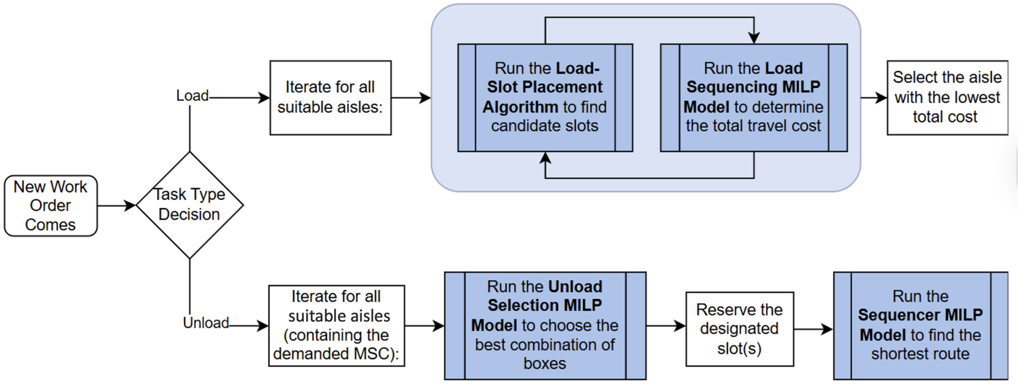


Figure 3: Solution Approach Flowchart

When a new work order arrives, the system first determines whether it is a load or unload task. For load operations, feasible aisles are evaluated based on availability and box type compatibility. Candidate storage locations are generated through the Load-Slot Placement Algorithm, and the most suitable aisle, slot, and task sequence are determined using the Load Sequencing Mixed-Integer Linear Programming (MILP) Model. For unload operations, candidate aisles containing the requested MSC are identified, and the Unload Selection MILP Model determines the most appropriate set of boxes to satisfy the demand. If necessary, tasks are divided into smaller sub-orders, selected slots are reserved to prevent conflicts, and the crane's updated task sequence is determined by the Sequencer MILP Model. Detailed descriptions of these models and the algorithm are provided in the following sections.

4.2 Mathematical Models

The first mathematical model is the Load Sequencing MILP Model, which minimizes total crane travel distance while determining the best insertion of a new load task into the existing sequence and selecting one candidate slot. The constraints ensure that all fixed tasks are visited exactly once, exactly one candidate slot is chosen, and the resulting tour is feasible and connected. The full formulation is provided in Appendix A.1.

The Unload Selection MILP Model is formulated as a knapsack-like model that selects the most appropriate subset of boxes containing the requested MSC to satisfy the demand of an unload work order (Polten and Emde, 2022). The objective favors older and fuller boxes while penalizing excessive box retrieval, long travel distances, and surplus quantity. The constraints ensure that the demanded quantity is met and any surplus is explicitly captured. The full formulation is provided in Appendix A.2.

The Sequencer Model is formulated as a rolling-horizon (MILP) model that determines the execution order of a number H of oldest pending tasks by minimizing total empty travel distance between consecutive tasks. The constraints ensure that each task in the horizon is executed exactly once and that the resulting sequence is feasible and connected. By repeatedly optimizing only the oldest pending tasks, the model preserves First In First Out (FIFO) logic while maintaining computational tractability. The full formulation is provided in Appendix A.3.

4.3 Algorithms

A turnover-based storage assignment methodology was developed to place frequently retrieved items in more accessible locations and thereby reduce travel time. Using the past ten days of historical data, products were grouped according to retrieval frequency through K-means clustering. This approach was preferred over quantile-based classification, since preliminary analysis showed an exponential-like usage distribution that made fixed splits less effective. The methodology is designed to update periodically in order to reflect changing demand patterns.

For load operations, the system uses a heuristic Load-Slot Placement

Algorithm that assigns storage locations based on turnover rate and slot accessibility. For each incoming item, an ideal storage depth is determined from its turnover rate, and all feasible empty slots are scored according to the difference between their actual depth and this ideal position. In this way, high-turnover items are placed closer to I/O points, while lower-turnover items are assigned to less accessible locations.

5 Validation

The proposed optimization model was validated against operational data from the company's live AS/RS facility, covering a week from January 2nd to January 9th, 2026.

To ensure a realistic comparison, a 50% normalization factor was applied to real-system timing and queue metrics prior to benchmarking. The value of this factor was determined in consultation with company experts. This adjustment reflects operational noise not captured by the simulation: AS/RS breakdowns and unplanned stoppages, and conveyor congestion at the I/O point. The factor is applied to the real system's baseline so the improvements reported below represent a conservative lower bound.

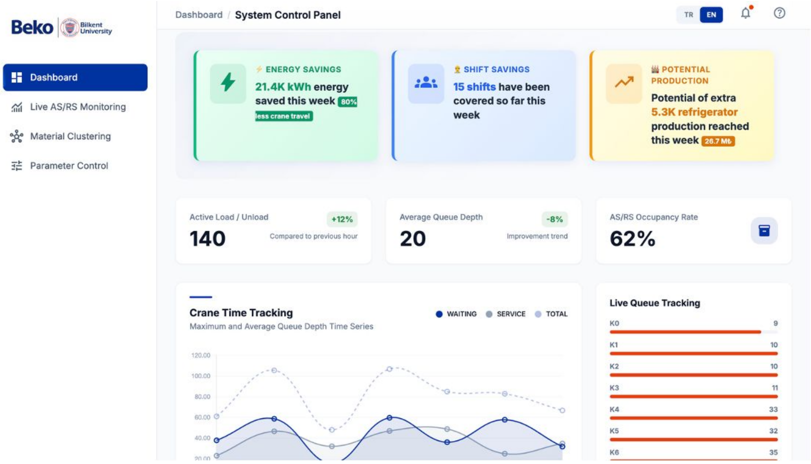
In terms of performance metrics, the proposed system reduced the average queue depth at the crane conveyors by 52% relative to the adjusted real-system baseline. The improvement in task scheduling further translated into a 40% reduction in average crane waiting time. The item placement logic ensured that frequently requested items were stored closer to the I/O point, cutting average crane travel distance per task by 39%. While queue depth and waiting time metrics are subject to operational variables such as equipment downtime and crane speeds, the 39% reduction in travel distance represents a fundamental structural improvement. This metric provides a deterministic gain in efficiency, independent of external system fluctuations. Furthermore, tasks were distributed evenly across the aisles. Together, these results confirm that the proposed model delivers substantial efficiency gains within the existing hardware infrastructure, even when evaluated under deliberately conservative assumptions.

6 Implementation and Pilot Study

The implementation phase was carried out in close collaboration with the company. System logic documentation, annotated pseudo code, technical report, user manual, and detailed flowcharts were prepared and delivered to the company's IT department to support technical integration. Meetings were held to clarify operational constraints, finalize integration requirements, and align the deployment schedule with the factory's existing infrastructure.

Building on the initial one-week validation, a full-scale pilot study was subsequently conducted using one complete month of real operational data, spanning January 2nd to February 4th, 2026. The simulation processed 104,309 work orders across seven crane aisles over a 33-day period. Applying the same 50% conservative adjustment described previously, the proposed model reduced average crane waiting time by 47%, average queue depth by 41%, and average travel distance per task by 25%. These improvements held consistently across all days of the week and all five weeks of the study period, confirming that the results are not driven by any single low-demand period or outlier week.

The main deliverables of the project included optimization modules compatible with the existing AS/RS structure, software code, and a user interface supported by a Python based Decision Support System (DSS) that enabled real-time coordination of storage assignment and crane scheduling within the AS/RS. The DSS was integrated with factory data and background optimization models. The interface was organized into four modules: the System Control Panel for executive KPI tracking and crane monitoring in Figure 4; Live Monitoring for corridor heatmaps and slot occupancy in Figure 5; Periodical Material Clustering for SKU dataset analysis using K-Means; and Parameter Control for dynamic adjustment of algorithmic weights.



21.4K kWh energy saved this week 80% less crane travel

15 shifts have been covered so far this week

Potential of extra 5.3K refrigerator production reached this week 26.7 M₺

Active Load / Unload: 140 (+12% Compared to previous hour)

Average Queue Depth: 20 (-8% Improvement trend)

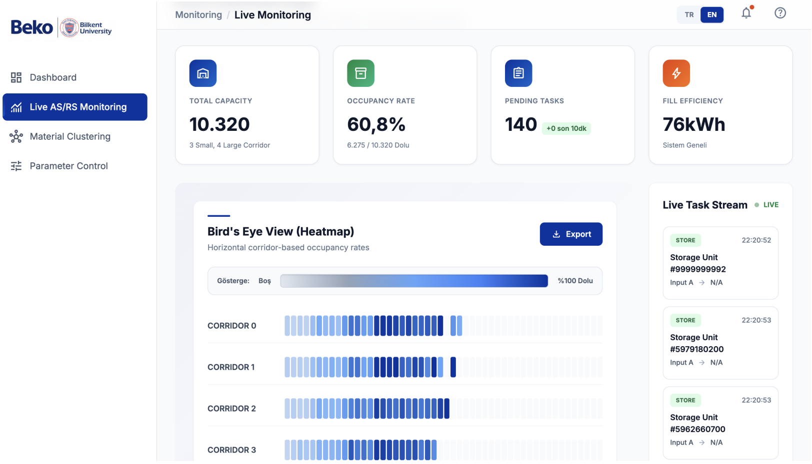
AS/RS Occupancy Rate: 62%

K0	9
K1	10
K2	10
K3	11
K4	33
K5	32
K6	35

Figure 4: Decision Support System: Dashboard

7 Benchmarking and Benefits

The proposed framework replaces experience-based heuristics with a data-driven, optimization-based approach for AS/RS operations. Upon receiving



TOTAL CAPACITY: 10.320 (3 Small, 4 Large Corridor)

OCCUPANCY RATE: 60,8% (6.275 / 10.320 Dolu)

PENDING TASKS: 140 (+0 son 10dk)

FILL EFFICIENCY: 76kWh (Sistem Geneli)

Bird's Eye View (Heatmap)

Horizontal corridor-based occupancy rates

Live Task Stream • LIVE

STORE 22:20:52
Storage Unit #9999999992
Input A → N/A

STORE 22:20:53
Storage Unit #5979180200
Input A → N/A

STORE 22:20:53
Storage Unit #5962660700
Input A → N/A

Figure 5: Decision Support System: Live Monitoring

a work order, the system activates specific decision modules: storage slots are scored based on demand frequency and proximity to output points, while retrieval tasks are prioritized by balancing stock age, fill levels, and location. By dynamically re-ordering the crane's workload to minimize travel distance and preserve fulfillment sequences, the system significantly reduces unnecessary movement and wait times. Ultimately, this coordinated structure improves operational efficiency by reducing unnecessary crane movement, shortening waiting times, and supporting smoother material flow to production lines.

Benchmark results indicate that the proposed model can significantly improve AS/RS performance compared to the current system. The solution reduces average queue depth by around 41%, average crane travel distance by 25%, and average crane waiting time by 47%, leading to faster response times and more balanced crane utilization. Beyond operational improvements, the project creates a substantial financial impact. Based on annualized estimates, the proposed system provides approximately 807,600 kWh of energy savings, corresponding to nearly \$63,810. In comparison, labor efficiency gains are estimated to generate an additional \$86,132 in annual value as shown in Table 1. Together, these improvements highlight that project delivers both immediate operational benefits and long-term economic value for the company.

8 Conclusion

This project has successfully optimized the AS/RS operations at the Arçelik Eskişehir Refrigerator Plant by integrating storage location assignment and crane sequencing, fully satisfying the organization's expectations for opera-

Table 1: Benchmark Results and Economic Impact

Metric	**Current System**	**Proposed Model**	**Improvement**
Average Waiting Time	425 – 476 Sec	∼225 – 252 Sec	%47 Reduction
Average Travel Distance	13.6 Unit	10.2 Unit	%25 Reduction
Average Queue Depth	5.1 – 6.8 Orders	3.0 – 4.0 Orders	%41 Reduction
Financial & Energy Impact	**Annual Savings**	**Economic Value**	**Total Benefit**
Energy Consumption	807,600 kWh	$63,810	
Labor Efficiency	570 Shifts	$86,132	
Total Annual Impact			**$149,942**

tional excellence, as confirmed by positive company feedback. By replacing experience-driven heuristics with a Decision Support System (DSS) utilizing turnover-based K-means clustering and MILP models, the study achieved a 25% reduction in crane travel distance, a 41% reduction in queue depth, and a 47% decrease in crane waiting time. Beyond these technical KPIs, the solution provides approximately $150,000 in annual economic value through energy and labor efficiencies and is currently ready for full-scale integration into the factory's infrastructure. Future work will focus on scaling this model to the other AS/RS unit within the Eskişehir plant and leveraging the identification of breakdown and downtime causes to maximize the system's feeding capacity under ideal operating scenarios.

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Appendices

A Mathematical Model Formulations

A.1 Load Sequencing MILP Model

Notation	Definition
$N = \{0, 1, \ldots, m, m+1, \ldots, n\}$	Set of all tasks, 0 being the crane's initial position.
$C = \{m+1, \ldots, n\}$	Cluster of candidate slots.
$V_{\text{fixed}} = \{0, 1, \ldots, m\}$	Set of fixed (existing) tasks.
d_{ij}	Chebyshev distance, travel cost from the end state of task i to the start state of task j.
$X_{ij} \in \{0, 1\}$	Binary variable equal to 1 if the crane moves directly from task i to task j, and 0 otherwise.
$u_i \geq 0$	Continuous auxiliary variable.

$$\text{Minimize} \quad \sum_{i \in N} \sum_{\substack{j \in N \\ j \neq i}} d_{ij} X_{ij} \tag{1}$$

$$\text{s.t.} \quad \sum_{\substack{j \in N \\ j \neq i}} X_{ji} = 1 \qquad \forall i \in V_{\text{fixed}} \tag{2}$$

$$\sum_{\substack{j \in N \\ j \neq i}} X_{ij} = 1 \qquad \forall i \in V_{\text{fixed}} \tag{3}$$

$$\sum_{i \in N \setminus C} \sum_{j \in C} X_{ij} = 1 \tag{4}$$

$$\sum_{i \in C} \sum_{j \in N \setminus C} X_{ij} = 1 \tag{5}$$

$$\sum_{\substack{j \in N \\ j \neq k}} X_{jk} = \sum_{\substack{j \in N \\ j \neq k}} X_{kj} \qquad \forall k \in C \tag{6}$$

$$X_{ij} = 0 \qquad \forall i, j \in C \tag{7}$$

$$u_i - u_j + |N+1| X_{ij} \leq |N+1| - 1 \qquad \forall i, j \in N \setminus \{0\},\ i \neq j \tag{8}$$

$$1 \le u_i \le |N+1| - 1 \qquad \forall i \in N \setminus \{0\} \tag{9}$$

$$X_{ij} \in \{0,1\}, \quad u_i \ge 0 \qquad \forall i, j \in N \tag{10}$$

- The objective (1) minimizes total crane travel distance.
- Constraints (2) and (3) ensure that each fixed task is visited once.
- Constraints (4),(5), and (6) ensure that one candidate slot is selected.
- Constraint (7) prevents intra-cluster movements.
- Constraints (8) and (9) eliminate subtours and ensure connectivity.
- Constraint (10) defines the domains.

A.2 Unload Selection MILP Model

Notation	**Definition**
$I = \{0, 1, \ldots, n\}$	Set of all available boxes containing the required MSC.
D	Demanded quantity.
Q_i	Quantity in box i.
A_i	Age score of box i.
Z_i	Distance score of box i.
F_i	Fill score of box i.
w_{age}	Weight for age.
w_{box}	Penalty for each selected box.
w_{dist}	Weight for distance.
w_{fill}	Weight for fill level.
w_{surplus}	Penalty for surplus quantity.
$X_i \in \{0,1\}$	Binary variable, 1 if box i is selected, 0 otherwise.
$S \ge 0$	Continuous variable, surplus quantity.

$$\begin{aligned}
\text{Maximize} \quad & w_{\text{age}} \sum_{i \in I} A_i X_i + w_{\text{fill}} \sum_{i \in I} F_i X_i - w_{\text{box}} \sum_{i \in I} X_i \\
& - w_{\text{dist}} \sum_{i \in I} (1 - Z_i)\, X_i - w_{\text{surplus}}\, S && (1) \\
\text{s.t.} \quad & \sum_{i \in I} Q_i X_i \ge D && (2) \\
& \sum_{i \in I} Q_i X_i - D = S && (3) \\
& S \ge 0, \quad X_i \in \{0,1\} \quad \forall i \in I && (4)
\end{aligned}$$

- Objective function (1) favors older and fuller boxes while penalizing long travel, multiple retrievals, and surplus.
- Constraint (2) ensures that total retrieved quantity meets demand.
- Constraint (3) defines surplus as the excess over demand.
- Constraint (4) defines the domains.

A.3 Sequencer MILP Model

Notation	**Definition**
$K = \{0, 1, \ldots, H\}$	Set of tasks in the horizon.
$N = \{0\} \cup K$	Set of all tasks, 0 is the current crane position.
C_{ij}	Travel cost from task i to j.
$X_{ij} \in \{0, 1\}$	Binary variable, 1 if task j follows task i.
$u_i \geq 0$	MTZ auxiliary variable.

$$\text{Minimize} \quad \sum_{i \in N} \sum_{\substack{j \in N \\ j \neq i}} C_{ij} X_{ij} \tag{1}$$

s.t.

$$\sum_{\substack{j \in N \\ j \neq i}} X_{ji} = 1 \qquad \forall i \in N \tag{2}$$

$$\sum_{\substack{j \in N \\ j \neq i}} X_{ij} = 1 \qquad \forall i \in N \tag{3}$$

$$u_i - u_j + |N| X_{ij} \leq |N| - 1 \qquad \forall i, j \in N \setminus \{0\},\ i \neq j \tag{4}$$

$$1 \leq u_i \leq |N| - 1 \qquad \forall i \in N \setminus \{0\} \tag{5}$$

$$X_{ij} \in \{0, 1\}, \quad u_i \geq 0 \qquad \forall i, j \in N \tag{6}$$

- The objective (1) minimizes total empty travel.
- Constraints (2) and (3) ensure each task is executed once.
- Constraints (4) and (5) eliminate subtours.
- Constraint (6) defines variable domains.

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