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INTELLIGENT 3D SPACE OPTIMIZATION FOR LOGISTICS OPERATIONS

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Abstract: In modern logistics operations, effective capacity utilization in warehouse, palletizing, and transportation processes is one of the most critical objectives. Manual planning errors, inadequate rule-based approaches, and a lack of integration with enterprise systems are common issues encountered in traditional methods, which increase operational costs, lead to lost time, and negatively impact sustainability goals. This study proposes an intelligent software solution that utilizes heuristic, exact, and metaheuristic algorithms, supported by 3D visualization and ERP/WMS/TMS integration. The proposed system ensures optimal placement of products on pallets, containers, and vehicles, thereby increasing operational efficiency and contributing to the green transformation of logistics.
Keywords: 3D optimization, logistics, heuristic

INTRODUCTION

Increasing competition in global supply chains necessitates reducing costs and achieving sustainability goals in the logistics sector. Minimizing empty spaces, particularly during pallet, container, and vehicle loading processes, provides both economic and environmental benefits. However, current systems largely rely on manual planning or rule-based methods, resulting in inefficient capacity utilization, loading errors, and high operational costs [1].
In recent years, interest in optimization software in the logistics sector has increased as part of Industry 4.0 and digital transformation. Existing methods often rely on manual planning or simple rule-based algorithms. However, these methods are both time-consuming and inadequate for complex product diversity. Furthermore, most of the software used is not integrated with enterprise systems, such as ERP, WMS, or TMS, leading to disruptions in data flow and difficulties with real-time decision-making. Furthermore, sustainability pressures are driving the need to reduce carbon footprints [1-3].
The container and vehicle capacity optimization problem is closely related to the classical 3D Bin Packing Problem (3D-BPP). In the literature, this problem cannot be solved with exact methods in large-scale examples due to its NP-hard nature, so heuristic and metaheuristic algorithms are preferred [4,5]. Especially in the logistics sector, the efficient packing of loads of varying sizes and weights into containers and pallets plays a critical role in both reducing operational costs and ensuring environmental sustainability [6].
The Container Loading Problem (CLP) and the Bin Packing Problem (BPP) are optimization problems that have long been the subject of research attention. While exact methods (e.g., integer programming) were proposed in early studies, computational costs remained very high for large-scale problems [7]. Therefore, in recent years, heuristic and metaheuristic methods (genetic algorithms, tabu search, simulated annealing, etc.) have become increasingly preferred [5,6,8].
Furthermore, incorporating not only theoretical optimization but also real-world constraints into the model has become important. Ignoring factors such as product fragility, stacking rules, weight balance, and regulations reduces the applicability of solutions [9,10].
Recent studies emphasize the need to consider AI-supported optimization approaches in logistics processes in conjunction with green transformation goals [1].

The intelligent 3D optimization platform proposed in this study offers a solution that is both theoretical and applicable in the field. Thus, capacity planning in logistics is no longer merely a tool for reducing operational costs but rather a strategic tool that serves sustainability and digital transformation goals.

MATERIAL AND METHODS

Problem State

In logistics and supply chain management, the Container Loading Problem (CLP) and the Multi-dimensional Bin Packing Problem (BPP) are among the most well-known NP-hard optimization problems [5,7]. The primary objective is to minimize void volume and maximize capacity utilization by placing products of varying sizes and constraints into vehicles, containers, or pallets in accordance with the limited volume, weight, and stacking conditions. This problem directly impacts not only operational efficiency but also cost reduction and sustainability objectives [10].

Mathematically, the problem can be formulated as follows: Products with dimensions (l_i, w_i, h_i), each denoted by $i = 1,2, \dots, n$ must be placed in containers of dimensions (L, W, H). Each product can be placed only once, and additional constraints, such as rotation, weight distribution, or fragility, must also be considered. The main optimization objective is to maximize the total volume used to increase the fill ratio within the container:

$$\max U = \frac{\sum_{i=1}^{n} V_i \times x_i}{V_c}, \tag{1}$$

Here, $V_i = l_i \times w_i \times h_i$ represents the product volume and $V_c = L \times W \times H$ represents the container volume. The decision variable $x_i \in \{0,1\}$ indicates whether the product is placed or not.

However, in real-world scenarios, volume constraints alone are not sufficient. For example, operational constraints such as weight constraints ($\sum w_i \times x_i \leq W_{max}$), product fragility (not placing heavy products on top), and delivery priority must be incorporated into the model [3,9]. This transforms the problem from a classical optimization problem into a highly constrained, multi-objective optimization problem. Therefore, the use of heuristic and metaheuristic methods for solving CLP/BPP provides more applicable and effective results, especially in large-scale logistics operations [8].

Method

The system proposed in this study proposes a multi-constrained, multi-objective optimization approach for optimizing container, pallet, and vehicle capacities in logistics operations. The developed method is based on a hybrid combination of heuristic, exact, and metaheuristic algorithms. The proposed solution method consists of four main components:

Table 1. *Methodological components of the proposed system*

Modules	Descriptions	Methods
Data Preprocessing	Modeling of product dimensions, weights, and operational constraints	Database, preprocessing algorithms
Optimization Engine	Generation of loading plans.	Exact, Heuristic, and Metaheuristic
3D Visualization	Simulation of loading plans and operator support	3D modeling, visualization libraries
Integration Layer	ERP/WMS/TMS integration and reporting	API, web services

Among metaheuristic methods, Genetic Algorithm (GA) and Tabu Search (TS) are particularly prominent. In GA, each chromosome represents the order of placement of products within the container. Crossover and mutation operators enable efficient scanning of the solution space by generating different loading scenarios [10]. In TS, a specific tabu list is maintained for each solution, preventing the algorithm from getting stuck in local optima [8].

RESULTS AND DISCUSSION

In this study, our algorithmic approach consists of preprocessing, constructive, and improvement phases. In the preprocessing phase, the items are sorted based on volume, weight, and stackability criteria, thus narrowing the search space during the placement process. In the constructive phase, an initial solution is generated using potential placement points for the boxes ("pivot points") and maximal space management strategies [8]. In the improvement phase, solution quality is enhanced by applying metaheuristics such as Variable Neighborhood Descent (VND) or GRASP (Greedy Randomized Adaptive Search Procedure) [11, 12].

In the model proposed by Zanchetta (2025), the concept of multi-objective optimization is particularly prominent. Similarly, our study addresses two main objectives:

1. Maximizing volume utilization – reducing transportation costs by minimizing the number of pallets/containers used.
2. Considering fragility constraints – placing loads in accordance with stacking rules to prevent product damage.

The Pareto optimality approach was adopted for optimizing this multi-objective structure, aiming to achieve solutions that balance different objectives [13]. Thus, solutions are produced that consider not only capacity utilization but also operational safety and customer satisfaction. Figure 1 shows an example of single and mixed packaging.

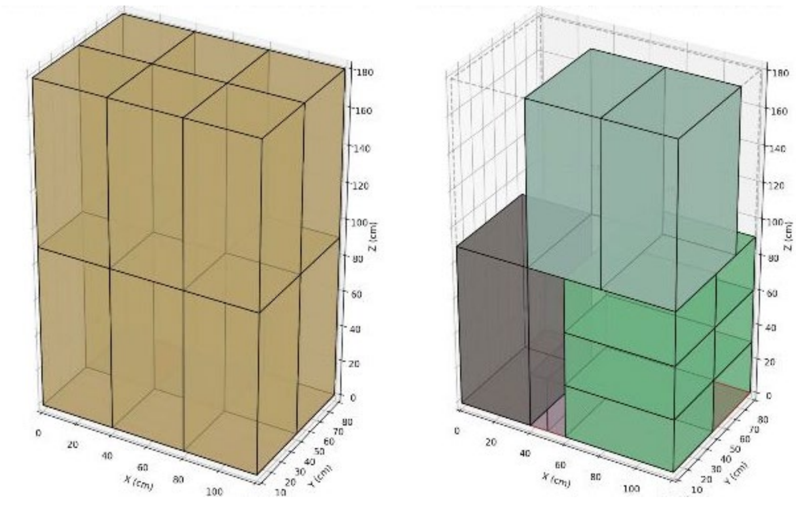

Fig. 1. *An example of single and mixed packaging*

CONCLUSION

This study presents an AI-based software approach that optimizes capacity utilization in logistics operations. Through algorithmic optimization, 3D visualization, and enterprise system integration, the system increases both theoretical efficiency and field applicability. This enables logistics planning processes to be faster, more accurate, more cost-effective, and more sustainable.

Studies demonstrate that logistics optimization systems not only provide cost advantages but can also directly contribute to sustainability goals. Future research is expected to focus more on the operational flexibility, real-time integration, and environmental impact reduction dimensions of AI-supported optimization models.

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