▪ Journal of Competitiveness

An optimization approach for an order-picking warehouse: An empirical case

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Abstract

Order-picking optimization in a business sustainable competitiveness context is challenging due to prior studies focusing on theoretical model development with unrealistic assumptions in their algorithms and methodological validation, often neglecting practical concerns. This paper improves order-picking operations by employing combinatorial optimization as a travelling salesman problem and class-based dedicated storage models for the ATP company. The paper's originality and novelty lie in bridging the gap between academia and management, presenting an effort to connect theoretical concepts with practical optimization in order-picking warehouse operations in an environment of competitiveness. Realistic data and LINGO software were employed, revealing substantial improvements in the ATP warehouse operations through optimized pick path decisions embedded in warehouse layouts. This paper provides managerial tools for distance traveled optimization in the warehouse that yield competitive edges, enhanced supply chain efficiency and effectiveness, as well as other positive impacts on social, and environmental concerns such as labor safety, customer satisfaction, energy consumption, and CO2 emission. The paper also outlines future research directions to advance warehouse management and address sustainable competitiveness challenges, adding a new dimension to the original research.

Keywords: *Class-based Dedicated Storage, Combinatorial Optimization, Order Picking, Sustainable Competitiveness, Travelling Salesman Problem, Warehouse Layout*

JEL Classification: C61, L69, L89

Article history: Received: June 2023; Accepted: December 2023; Published: December 2023

1 INTRODUCTION

A warehouse in the supply chain acts as a buffer that allows companies to quickly react to fluctuation or uncertainty in the competitive market due to unexpectedly aggressive demand changes, especially in retail distribution and e-commerce (Çelik et al., 2022; Calzavara et al., 2019). Warehouse management is a critical element in maintaining supply chain efficiency for sustainable development in a competitive environment. Approximately 25% of logistics costs is accounted for by warehouse activities in which order picking constitutes around 55% of the warehouse operating costs, and travel time accounts for approximately 60% of the total time of order picking activities (Tompkins et al., 2010). In picker-to-parts systems, pickers walk through the picking area to collect the requested items. In parts-to-picker systems, automated cranes move along the aisle, retrieve unit loads, and bring them to a pick position. The travel time is an increasing function of the travel distance for the picker-to-parts order picking system. As a result, minimizing travel distance is the primary goal in warehouse design and operations optimization. Researchers agree that travel distance should be considered to optimize the picking path (De Koster et al., 2012).

https://doi.org/10.7441/joc.2023.04.09

Although most companies recognize warehouses as an essential supply chain element rather than a value-adding step, the warehouse is usually only invested in its basic storage infrastructure. Current, complex market conditions caused by e-commerce and globalization forced warehouses to handle large numbers of orders in short time windows (Vanheusden et al., 2022). The high demand and tight delivery schedules increase stress in the order-picking process (Guo et al., 2022; Jaghbeer et al., 2020; Shiau & Ma, 2014). Warehouse operations are considered crucial elements enabling inventory policy and warehouse layout, as well as order picking activities such as receiving, unloading, putting away, storing, order preparation, and transportation matched with the demands of customers (Altarazi & Ammouri, 2018). Warehouse design is an interdependent cluster of decisions at the strategic, tactical and operational levels (Vanheusden et al., 2022).

Indeed, warehouses are increasingly piece-picking rather than handling larger units. Picking a high number of stock-keeping units (SKUs) directly from bulk storage is often inefficient, since it takes more time and effort to determine, generates more wasted travel between the picking interfaces, and results in much space being lost due to numerous broken pallets (Bahrami et al., 2019). The picking process should be investigated within a system context. To reduce warehousing costs in the long run and decrease the time required to retrieve goods and prepare shipping units, careful warehouse layout design is required (Çelik et al., 2022). A pronounced research-practice gap persists, as prior studies predominantly emphasized theoretical model development, frequently incorporating unrealistic assumptions in algorithms and methodological validation, while neglecting practical concerns. Consequently, the adoption of these models into company operations poses challenges (Casella et al., 2023; Vanheusden et al., 2022). This paper is an effort to link researchers with managers in optimizing picking by applying mathematical models and algorithms for warehouse operations in a company focusing on picker-to-parts operation, which still accounts for most of order-picking systems (Zhang & Gao, 2022). The case study is known as ATP, as the company's name and other information that would allow for its identification have been changed; it is the most extensive network provider in Vietnam and acted as a distribution center with 4 main product types. The main problems of this case are ineffective warehouse leads to weak performance in order-picking operations. The study re-layouts the allocations of goods more scientifically regarding picking path optimization of the ATP, reflected in effective and efficient supply chain performance geared towards sustainable competitiveness in three dimensions: economy, society, and environment. Hybrid models of class-based dedicated assignment (CDA) and the travelling salesman problem (TSP) are developed using the LINGO solver to optimize the distance that pickers must travel to collect an uncertain number of products over proposed warehouse layouts.

The remainder of the paper is organized as follows. The theoretical backgrounds are presented in Section 2. In Section 3, the case study is investigated, and research methodology and data collection are proposed. Section 4 presents the results and key findings. Discussion occurs and recommendations are made in Section 5. Section 6 gives conclusions and suggests avenues for further research.

2 THEORETICAL BACKGROUNDS

For reaching the best level of warehouse productivity performance, the keyword phrases 'logistics and supply chain', 'warehouse design and management', 'order picking', 'facilities layout and location', etc., are utilized thoroughly in research engines such as Google Scholar, Scopus, and Web of Science databases.

2.1 LOGISTICS AND SUPPLY CHAIN MANAGEMENT

Logistics and supply chain management is a vast field that many researchers have focused on, providing various definitions, such as, "supply chain management is primarily concerned with the efficient and effective integration of suppliers, manufacturers, distributors, and customers network by planning, organizing, directing, controlling, and managing flows of information, materials, and services so that merchandise is produced and distributed in the right quantities, to the suitable locations, at the right time, and to minimize total system costs subject to satisfying service requirements" (Simchi-Levi et al., 2008). Hugos (2018) differentiated logistics (internal organizational activities) from supply chains (collaborative networks), while supply chain management encompasses broader functions. Orkestra (2023) notes challenges in global supply chain management due to various factors like the Ukraine war, rising energy prices, and COVID-19. This has prompted a need for industry-wide digitalization to adapt to customer needs and enhance supply chain performance, with a focus on warehouse efficiencies.

2.2 WAREHOUSE AND WAREHOUSE MANAGEMENT

According to Hugos (2018), warehouses are among the five critical components in a primary supply chain, including production, inventory, location, transportation, and information. Warehouse management significantly influences supply chain performance, serving the primary purpose of holding goods until needed. Modern warehouses, beyond storage, contribute to the sustainable competitiveness of companies by performing value-added activities functioning as distribution centers (Bottani et al., 2019). Warehouse optimization is crucial for effective logistics and supply chain management, involving a set of strategic-tactical-operational decisions on warehouse size, layout, equipment, operational strategy, storage assignment, and order-picking policies.

2.3 WAREHOUSE LAYOUT DESIGN

Warehouse layout is described as "the physical arrangement of storage racks, loading and unloading areas, equipment, offices, rooms, and all other facilities" (Waters, 2003).

Optimizing the picking process hinges on the warehouse layout, whether conventional (rectangular) with parallel aisles or not. In a conventional layout, pick aisles are parallel, allowing quick lane changes (Bottani et al., 2019). A proper warehouse design should ensure smooth material flow, minimize traveled distance, allocate high-bay space for high storage needs, and reserve low-bay space for labor-intensive processes with adequate aisle space for equipment movement.

For an efficient internal layout design, factors to consider include the number and location of docks or depots (I/O points), the number of blocks and aisles, and the dimensions of aisles between blocks in a picking area (De Koster et al., 2012). Dock location principles assess product popularity by analyzing the ratio of loads (T_j) to bays (S_j) per month (T_j/S_j), known as the activity-to-space ratio (Tompkins et al., 2010). Combining product volume and picking frequency allows for a systematic layout based on item popularity. Warehouse design significantly impacts order picking travel distance, emphasizing the connection between layout and travel distance.

2.4 STORAGE POLICY

To fulfill customer orders, in most cases, items (SKUs) need placement in storage before picking. Storage policies, such as random storage, family-grouped storage, and class-based storage (ABC-storage), guide the assignment of goods to locations (De Koster et al., 2012; Tompkins et al., 2010). The random storage policy involves allocating incoming pallets to randomly chosen available slots. Family-grouped storage minimizes travel distance by storing SKUs likely to appear together. Class-based storage follows the Pareto rule (ABC classification) and allocates classes to specific regions, combining the advantages of random storage for space efficiency and strategic placement for fast-moving SKUs near *I*/*O* points.

2.5 ORDER PICKING

Order picking involves selecting products from storage to fulfill customer orders, representing the most labor-intensive and costly warehouse activity (Quader & Castillo-Villar, 2018). Managers seek streamlined order-picking policies based on specific scenarios and technology. Picker-to-parts, parts-to-picker, and put techniques (pick-and-sort, automated picking, etc.) classify order picking by human and product movement (Sheu & Choi, 2022; Marchet et al., 2015). The picker-to-part system, the most common, emphasizes minimizing travel time, which accounts for 50-60% of order-picking time (De Koster et al., 2012), motivating warehouse design and optimization efforts.

2.6 TRAVELING SALESMAN PROBLEM

The TSP states that given *n* cities, a salesman is required to visit each of *n* cities exactly once, starting from any city and returning to the original place of departure with a minimum-distance tour. The notation of distance can be replaced by cost or time. The problem is symmetric if $d_{ij} = d_{ji}$. Otherwise, it is asymmetric; triangle inequality is satisfied, if $d_{ik} \leq d_{ij} + d_{jk}$. Generally, the well-known TSP is an NP-hard and one of the most combinatorial optimization problems.

The complexity of the TSP has led to the exploration of various exact methods, including branch and bound, branch and cut, and dynamic programming (Sahputra et al., 2016). Heuristic and metaheuristic algorithms like *k*-opt, Lin and Kernighan and genetic algorithms, are employed for effective solutions in reasonable computational time for significant TSP problems (Davendra, 2010; Itoh, 2010). TSP finds applications in diverse fields such as distribution, warehousing, order picking, scheduling, and routing. Researchers have recently applied TSP to solve order-picking problems (D'Haen et al., 2022; Zhang et al., 2022; Füchtenhans et al., 2021; Briant et al., 2020).

2.7 SUSTAINABLE COMPETITIVENESS

Sustainable competitiveness, as defined by the World Economic Forum (2015), refers to the capability of establishing a framework of institutions, policies, and visions facilitating the long-term development of a company or nation, ensuring economic, social, and environmental sustainability (Doyle & Perez-Alaniz, 2017). Sustainability is vital for creating value, driving innovation, and advancing both individual and societal economies. Recently, culture has gained recognition as the fourth dimension of sustainable development (Lazar & Chithra, 2022). Competitiveness in this context pertains to the degree of productivity, emphasizing cost-efficiency or the capability of nations or companies to compete in the global market. There have been numerous studies on how to adopt sustainable and green mindsets in various industries such as sustainable logistics, supply chains, and production (Luu et al., 2023; Sarkis et al., 2020), as well as in a broader sustainable competitiveness context (Luu & Chromjaková, 2023).

3 RESEARCH METHODOLOGY AND DATA COLLECTION

3.1 CASE STUDY INVESTIGATION

ATP, a networking equipment provider in Vietnam, manages goods receipt and sales, overseeing logistics from Hong Kong to Vietnam, with a focus on 44 SKUs coded for anonymity (Appendix B). Warehouse details are summarized in Table 1, featuring fixed dimensions of 24m36m, bay dimensions of 2m2m, and a 2m aisle width. Random storage of products in the warehouse leads to inefficient picking paths. During high-demand seasons, ATP hires additional workers for box loading. Equipment used in the warehouse poses risks to products and laborers, increasing the likelihood of returned merchandise. The study identifies two main operational problems at ATP.

a. Warehouse Layout Design

- *Door locations:* the current warehouse has two doors but serves as 1 dock only, the main door is used for in/out workloads, while the remainder is treated as an emergency door.
- *Goods allocations:* ATP goods placing seems quite naïve, block stacking is used.
- *Height utilization* is restricted because of the fixed building (8m), which cannot use shelving for higher storage.
- *Material handling equipment* mainly runs manually and is time-consuming.

b. Order Picking Operations

- *Order picking tours:* the observation with the current layout reflects the picker-to-part system. The existing process of picking items for shipping consumes much time, movement, and effort. The picking path method is not applied for better performance.
- *Operational efficiency:* there are not any established parameters, key performance indices (KPIs), scores, or policies in terms of evaluating how well the warehouse has been operated.
- *Risk of RMA* (Return Merchandise Authorization): ATP is not allowed to discard the returned product or ship it back to headquarters in Hong Kong. The warehouse used more space for carrying them.

Tab. 1 – Warehouse information. Source: own research

Warehouse Layout Design	Layout (24m*36m)	No. of the doors (*I*/*O*)	1
		Height restriction	8m (meters)
		Goods allocating policy	Randomized, block stacking
	Equipment	Material handling equipment	Casual trolley
		Storage equipment	Wooden pallets
		Automation level	0
Warehouse Operations		Picking path	No proper treatment
		Parameters for WH efficiency	0
		RMA units	No proper treatment

Under the requirement of the ATP management board, this study optimizes the picking path embedded in ATP warehouse layouts, fostering a sustainable supply chain network for competitive advantages in the global market. The study seeks mainly operational benefits but also addresses social concerns related to labor health and safety, contributing to customer satisfaction. Furthermore, it addresses environmental considerations by reducing traveled distance, thereby lowering energy usage and associated CO2 emissions.

3.2 METHODOLOGY

This study introduces a hybrid model, merging class-based dedicated assignment (Tompkins et al., 2010) with a symmetric travelling salesman problem model. In detail, CDA is utilized for layout generation, followed by a TSP algorithm to propose feasible or near-optimal picking paths. Rectilinear travel is employed, measured between the centroids of storage bays.

No indication of which algorithm and solver offers the best critical path exists. LINGO is a well-known software for solving linear programming (LP), NP, stochastic programming, and global optimization. Regarding modeling of supply chain logistics, LINGO is a strong solver for a combinatorial optimization NP-hard problem such as TSP. Thus, LINGO is considered a sufficient solver over others, such as IBM ILOG CPLEX. The research procedure is summarized in Figure 1.

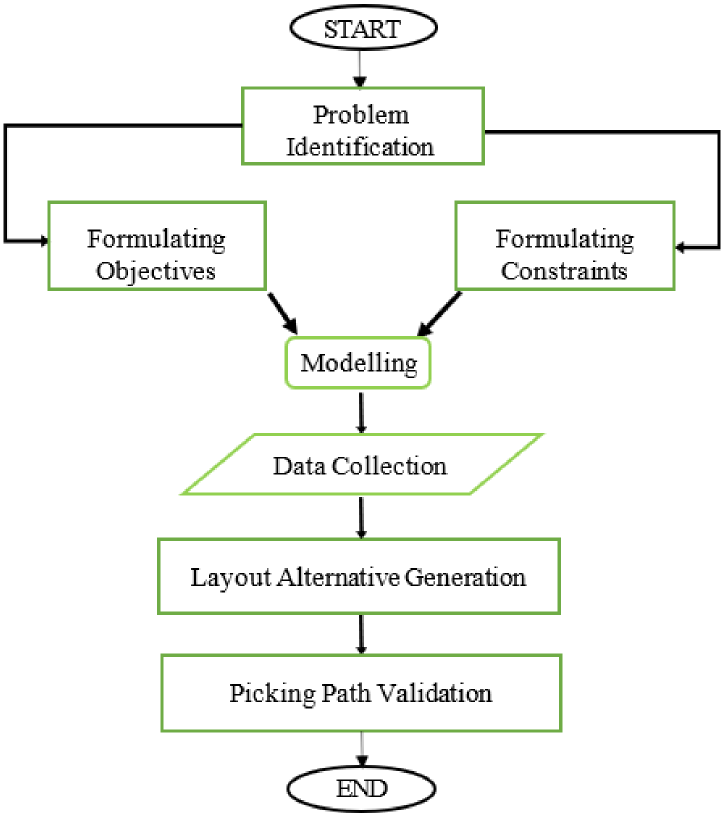


Fig. 1 – Research procedure. Source: own research

a. Mathematical Models

- **Class-based Dedicated Assignment Model**

The study considers the mathematical model of class-based dedicated assignment for determining an optimal dedicated storage layout, assuming rectilinear travel (Tompkins et al., 2010).

The study assumes the following parameters and variables:

q	*number of storage locations.*
n	*number of products.*
m	*number of input/output (I/O) points (docks).*
S_j	*number of storage locations required for product j.*
T_j	*number of trips in/out of storage for product j.*
p_j	*percentage of travel in/out of storage to/from I/O point i.*
d_{ik}	*distance required to travel from I/O point i to storage location k.*
x_{jk}	*= [0,1], 1 if product j is assigned to storage location k, 0 otherwise.*
$f(x)$	*average distance traveled.*

The objective function: Minimizing the expected distance traveled.

(3.1) $\boldsymbol{Minimize\ \sum_{j=1}^{n}\sum_{k=1}^{q}\frac{T_j}{S_j}\sum_{i=1}^{m}p_i d_{ik}\, x_{jk}}$

Subject to:

(3.2) $\boldsymbol{\sum_{j=1}^{n}x_{jk}=1,\ for\ k=1,\dots,q}$

(3.3) $\boldsymbol{\sum_{k=1}^{q}x_{jk}=S_j,\ for\ j=1,\dots,n}$

(3.4) $\boldsymbol{x_{jk}=(0,1),\forall j\ and\ \forall k}$

The study summarizes the assignment procedure to minimize the expected distance traveled (f_k) in Figure 2.

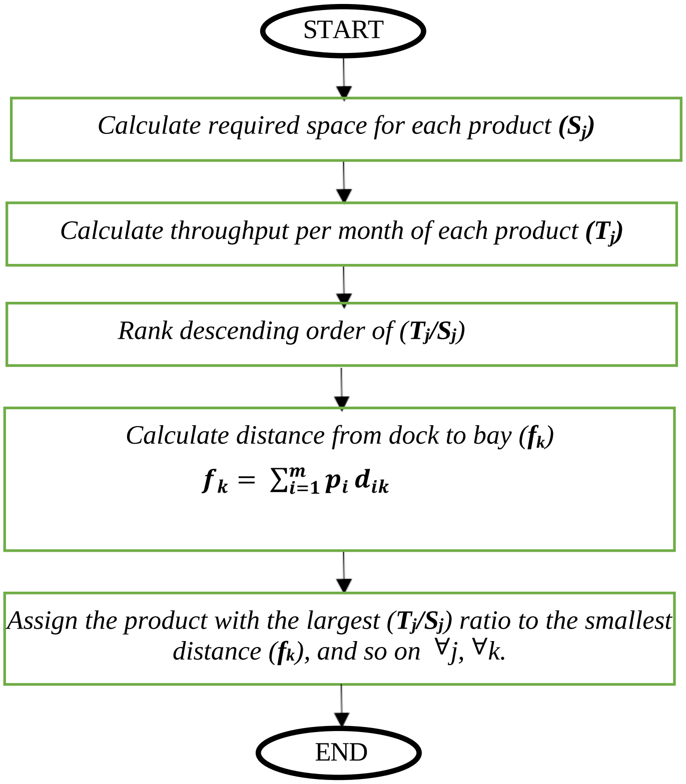


Fig. 2 – Dedicated Assignment Procedure. Source: own research

- **Traveling Salesman Problem Model**

Many TSP formulations are proposed (Davendra, 2010). This study mathematically states a symmetric TSP as follows: a picker must visit each of n storage locations, indexed by 1, …, n. He leaves from a depot (dock) indexed by I, visits each of the n other locations exactly once, and returns to depot I, and he must see no more than p locations in one tour. Finding such an itinerary that minimizes the total distance traveled is required. Given a 'distance matrix' $D = (d_{ij})$ where $d_{ij} = d_{ji}$ represents the distance between locations i and j, ($i \neq j = I, 1, \ldots, n$). The model uses the following notations:

Parameters and decision variables:

I	*start location index, i = I, 1, 2, …, n*
J	*destination index, j = I, 1, 2, …, n*
n	*number of order-picking locations, including depot I.*

x_{ij} = *[0,1], 1 if the path goes from location i to location j, 0 otherwise.*

The objective function: minimizing the total distance traveled.

(3.5) $\boldsymbol{Minimize}\ Z = \sum_{i\neq j=I}^{n}\sum_{j\neq i=I}^{n} d_{ij}\, x_{ij}$

Subject to:

(3.6) $\sum_{i\neq j=I}^{n} x_{ij} = 1, \qquad j = 1, 2, \ldots, n$

(3.7) $\sum_{j\neq i=I}^{n} x_{ij} = 1, \qquad i = 1, 2, \ldots, n$

(3.8) $u_i - u_j + p x_{ij} \le p - 1, \;\; i \neq j = 1, \ldots, \; n$

Where objective function (3.5) minimizes the total travel distance of the picker, constraints (3.6) and (3.7) represent the conditions that each location (other than *I*) is visited exactly once. The x_{ij} are non-negative integers and binary, i.e., the picker proceeds from location *i* to location *j* if and only if x_{ij} = 1. Inequality (3.8) with the arbitrary real numbers (u_i) plays a role like node potentials in a network, and the inequalities involving them eliminate tours that do not begin and end at the city *I* and tours that visit more than *p* cities. Next, subsection *b* clearly explains the TSP heuristic algorithm.

b. Traveling Salesman Heuristic Algorithm

The detailed procedure is developed below.

- *n locations.*
- *start from depot I.*
- *go to each n other location exactly once.*
- *return to depot I.*
- *produce a distance between location i and location j:* d_{ij}

✓ ***Each location j must be entered exactly once:***

(3.9) $\sum_{i\neq j,i=I}^{n} x_{ij} = 1$ ***for j = 1, …, n***

✓ ***Each location i must be exited exactly once:***

(3.10) $\sum_{j\neq i,j=I}^{n} x_{ij} = 1$ ***for i = 1, …, n***

✓ ***No sub-tours are allowed for any subset of locations S not including depot 0:***

(3.11) $\sum_{i,j\in S} x_{ij} \le |S| - 1$ ***for every subset S, where |S| is the size of S.***

✓ ***Alternatively, (3) may be replaced by***

(3.12) $u_j \ge u_i + 1 - (1 - x_{ij})p$ ***for j≠i = 1, 2, …, n***

Appendix C illustrates the algorithm running with the simple case of 4 SKUs (i.e., A1, B3, C1, and A7) in the LINGO solver. The distance matrix is randomly created. Highlighted values show the distance solution of 1,357 meters with sequence A1-C1-B3-A7-A1, concerning the objective function of minimizing the picking path.

3.3 DATA COLLECTION

Data collection and data analysis procedures are critical tasks for the methodology workflow. Data is collected, calculated, and confirmed from the operations and finance reports that were updated in October 2020, such as the list of SKUs, warehouse dimensions, number of docks (*I/O* point), number of aisles, number of receiving trips of each item per month, number of shipping trips of each item per month, storage space using of each item, current storage and picking policies (strategies), etc.

4 RESULTS AND KEY FINDINGS

4.1 WAREHOUSE LAYOUT DESIGN

a. Products Ranking

The class-based dedicated storage layout model ran with 44 SKUs the ATP warehouse holds. The result will show priority order of the items. The study especially considers the experience of the operations department to class several SKUs together as composited SKUs such as C1-C3-C4-C5-C6, C7-C8-C9-C11-C12, C13-C14-C15-C16-C17-C18, C19-C20-C21-C22, and C23-C24-C25 (Table 2). The T_j/S_j values are calculated based on the data of load per month (T_j) and the number of bay requirements (S_j) (Appendix *D*). Table 2 illustrates the rank of items corresponding to their own T_j/S_j ratios from largest to smallest. Moreover, the study assumes that class *A* consists of items that have about 80% of total activity-to-space. Class *B* and *C* combine items with lower activity and space with 15% and 5%, respectively.

Tab. 2 – *ABC* classification. Source: own research

No.	Random Code	Activity (T_j)	# of bays (S_j)	T_j/S_j	T_j/S_j (%)	Cumulative T_j/S_j	*ABC* classification
1	A7	11579	3	3859.7	8.76%	8.76%	***A***
2	B12	3717	1	3717.0	8.43%	17.19%	***A***
3	C23	3633	1	3690.0	8.37%	25.56%	***A***
4	C24	6					
5	C25	51					
6	B8	3054	1	3054.0	6.93%	32.48%	***A***
7	A5	10456	4	2614.0	5.93%	38.41%	***A***
8	B2	4774	2	2387.0	5.41%	43.83%	***A***
9	B1	2284	1	2284.0	5.18%	49.01%	***A***
10	C1	310	1	2243.0	5.09%	54.10%	***A***
11	C3	1449					
12	C4	173					
13	C5	157					
14	C6	154					
15	B6	2233	1	2233.0	5.07%	59.16%	***A***
16	A6	6671	3	2223.7	5.04%	64.21%	***A***
17	A4	12905	6	2150.8	4.88%	69.09%	***A***
18	C13	85	1	2056.0	4.66%	73.75%	***A***
19	C14	207					
20	C15	397					
21	C16	1064					
22	C17	179					
23	C18	124					

24	B4	3820	2	1910.0	4.33%	78.08%	*A*
25	B9	2923	2	1461.5	3.32%	81.40%	*B*
26	C10	1169	1	1169.0	2.65%	84.05%	*B*
27	B3	1060	1	1060.0	2.40%	86.45%	*B*
28	B5	1947	2	973.5	2.21%	88.66%	*B*
29	A1	9670	10	967.0	2.19%	90.86%	*B*
30	B11	724	1	724.0	1.64%	92.50%	*B*
31	C19	65	1	717.0	1.63%	94.12%	*B*
32	C20	453					
33	C21	76					
34	C22	123					
35	C7	43	1	662.0	1.50%	95.63%	*C*
36	C8	216					
37	C9	243					
38	C11	3					
39	C12	157					
40	A2	10302	16	643.9	1.46%	97.09%	*C*
41	B7	586	1	586.0	1.33%	98.42%	*C*
42	A3	5488	20	274.4	0.62%	99.04%	*C*
43	B10	270	1	270.0	0.61%	99.65%	*C*
44	C2	154	1	154.0	0.35%	100.00%	*C*
Total		**105154**	**85**	**44084**	**100%**		

b. Layout Generating

The study proposes and evaluates 3 alternatives to the warehouse layout described in Table 3, in which Map 0 is the current warehouse.

Tab. 3 – Layout Alternative. Source: own research

Alternative	Description
Map 0	The 1-door current warehouse layout (see Appendix *A*)
Map 1	A modified 1-door current warehouse layout
Map 2	A 2-door warehouse layout

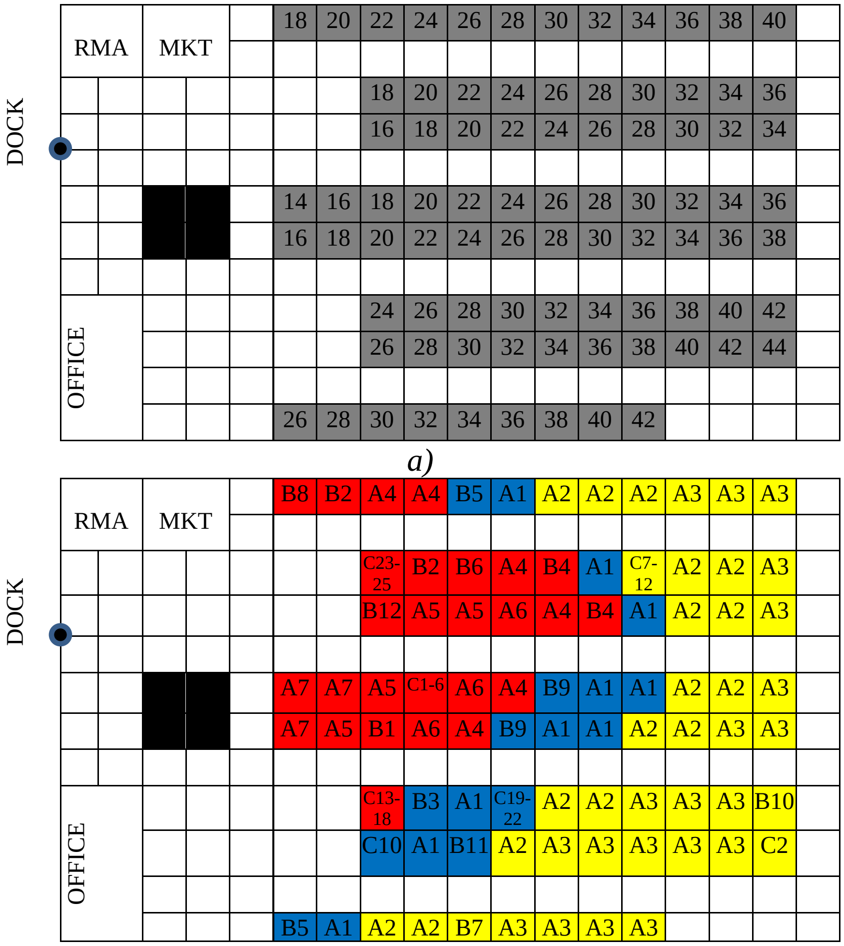
- **Map 1**

The locations and areas of current office departments remain the same as in Map 0. The total area spent for storage is 85 bays, with 2m2m for each bay, and all *I/O* activities are operated through 1 dock only; hence, the probability of computing is 100% for each bay.

The overall layout is modified into five storage lines with three double-sided designs, and the remainder are single storage lines. The aisles are created without dead-ends to ensure the constant flow of the in and out, preventing small-moving areas or congestion between orders and connecting the two sides among the double-sided storage lines.

This approach recommends creating a cross-docking area to utilize the main functions of any regular warehouse. The cross-docking areas of 4m4m, specifically located in front of the third storage line, are quite suitable to connect almost equally the lines of picking goods and the shipping path.

Appendix *E* shows the distance for each bay of Map 1, which is also reflected in Figure 3*a*. Following the procedure in Figure 2, Map 1 is assigned. SKUs belonging to class *A* in Table 2 are first with the smallest expected distance traveled (i.e., red areas with items having the most significant activity-to-space ratios). Those in green (class *B*) and yellow (class *C*) areas have moderate and low levels of activity-to-space ratios, respectively (Figure 3*b*).



RMA		MKT			18	20	22	24	26	28	30	32	34	36	38	40	
							18	20	22	24	26	28	30	32	34	36	
							16	18	20	22	24	26	28	30	32	34	
		■	■		14	16	18	20	22	24	26	28	30	32	34	36	
		■	■		16	18	20	22	24	26	28	30	32	34	36	38	
OFFICE							24	26	28	30	32	34	36	38	40	42	
							26	28	30	32	34	36	38	40	42	44	
					26	28	30	32	34	36	38	40	42				

a)

RMA		MKT			B8	B2	A4	A4	B5	A1	A2	A2	A2	A3	A3	A3	
							C23-25	B2	B6	A4	B4	A1	C7-12	A2	A2	A3	
							B12	A5	A5	A6	A4	B4	A1	A2	A2	A3	
		■	■		A7	A7	A5	C1-6	A6	A4	B9	A1	A1	A2	A2	A3	
		■	■		A7	A5	B1	A6	A4	B9	A1	A1	A2	A2	A3	A3	
OFFICE							C13-18	B3	A1	C19-22	A2	A2	A3	A3	A3	B10	
							C10	A1	B11	A2	A3	A3	A3	A3	A3	C2	
					B5	A1	A2	A2	B7	A3	A3	A3	A3				

b)

Fig. 3 – *a*) Map 1 with its distance; and *b*) Map 1 assigned. Source: own research

- **Map 2**

The structure of the new warehouse layout has entirely changed in this alternative by redesigning the layout for offices and other departments.

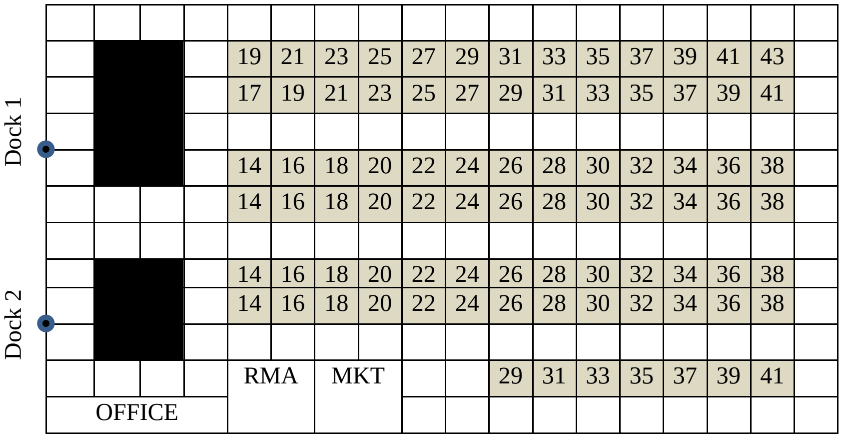
The number of doors is increased into two docks, assuming both docks equally display shipping and receiving functions (i.e., $p_1 = p_2 = 0.5$). The warehouse is now divided into four storage lines.

Detailed, there are equal double-sided lines with each line 26 meters in length. The remaining line is a single line of 14m.

Each storage line is also placed apart to create a clearance of 2m with two-way direction aisles approaching from both directions to utilize the movement within the warehouse.

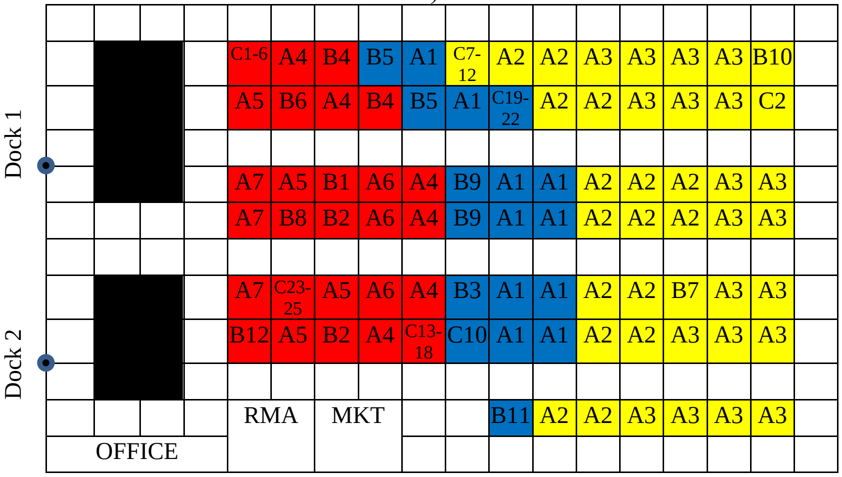
An expected distance travel of 44 SKUs in this scenario is calculated (Appendix *F*). Figures 4*a* and 4*b* describe Map 2 with its distance and storage location assigned for all 44 SKUs, respectively.

5



	19	21	23	25	27	29	31	33	35	37	39	41	43
	17	19	21	23	25	27	29	31	33	35	37	39	41
	14	16	18	20	22	24	26	28	30	32	34	36	38
	14	16	18	20	22	24	26	28	30	32	34	36	38
	14	16	18	20	22	24	26	28	30	32	34	36	38
	14	16	18	20	22	24	26	28	30	32	34	36	38
	RMA		MKT				29	31	33	35	37	39	41
OFFICE													

6 *a*)



	C1-6	A4	B4	B5	A1	C7-12	A2	A2	A3	A3	A3	A3	B10
	A5	B6	A4	B4	B5	A1	C19-22	A2	A2	A3	A3	A3	C2
	A7	A5	B1	A6	A4	B9	A1	A1	A2	A2	A2	A3	A3
	A7	B8	B2	A6	A4	B9	A1	A1	A2	A2	A2	A3	A3
	A7	C23-25	A5	A6	A4	B3	A1	A1	A2	A2	B7	A3	A3
	B12	A5	B2	A4	C13-18	C10	A1	A1	A2	A2	A3	A3	A3
	RMA		MKT				B11	A2	A2	A3	A3	A3	A3
OFFICE													

7 *b*)

8 Fig. 4 – *a*) Map 2 with its distance; and *b*) Map 2 assigned. Source: own research

8.1 PICKING PATH OPTIMIZATION

After properly reassigning products into new design layouts, the constructed distance matrix of SKU to SKUs is computed for each layout alternative. Purchase orders are randomly picked to determine the picking path over three maps solved in LINGO (Appendices *H*) by TSP heuristic algorithm to produce a feasible or near-optimal picking path.

For example, a packaging order of 7 SKUs (i.e., A1, B1, A4, B10, A2, A3, and C2) is used 10 times in the model (Appendix *G*), and the LINGO outcomes in average distance travel are 87m, 70m, and 60m over Map 0, Map 1, and Map 2, respectively (Table 4).

Tab. 4 – Order Picking Performance in 3 Maps. Source: own research

Orders	1	2	3	4	5	6	7	8	9	10	Average distance	Total distance	Improvement per map
Distance per order (m)	Map 0	100	90	66	72	116	94	96	64	79	88	87	865
	Map 1	80	76	60	66	28	82	66	72	80	92	70	702
	Map 2	48	68	48	40	50	88	64	64	60	68	60	598
Map 1 improvement	20%	16%	9 %	8 %	76%	13%	31%	-13%	-1 %	-5 %			
Map 2 improvement	52%	24%	27%	44%	57%	6 %	33%	0 %	24%	23%			

As a result, Map 2 has been chosen with the final percentage utilization and optimization of approximately 31% and 15% compared to Map 0 and Map 1, respectively (Table 5).

Tab. 5 – Pair comparison of Maps. Source: own research

Pair Comparison		Map 0	Map 1	Map 2
		87	70	60
Map 2	60	31%	15%	-
Map 1	70	19%	-	
Map 0	87	-		

Map 2 has been determined as the most significant ‘candidate.’ In addition, Map 1, which has minor modifications, is also considered a second choice, if ATP does not want to change department layouts, due to its overall improvement in the distance of 19% compared with Map 0. However, Map 1 negatively impacts running times of 8 to 10 (Table 4).

9 DISCUSSIONS AND RECOMMENDATIONS

This study concerns sustainable development in a competitive market that satisfies three dimensions: economy, environment, and society. For example, the renewed layout brings economic advantages for ATP by optimizing distances traveled, indirectly minimizing the logistic costs. Moreover, improved order picking ensures labor health, safety, and customer satisfaction, giving ATP a unique competitive advantage in the labor market. Reducing travel time and distance also caused lower used energy and CO2 emissions, alleviating environmental concerns.

Considering the case study investigation, the ATP warehouse currently utilizes wooden pallets. To address potential damage by termites and insects, the authors recommend appropriate disinfection measures and propose replacing casual trolleys with automated equipment, considering robotic technologies alongside human workers. Smart logistics, incorporating AI applications, is suggested for enhanced efficiency (Kalkha et al., 2023), with the interim use of pallet jacks to reduce employee effort. Automation and optimization facilitate agile responses to market demands (Grosse, 2023; Pasparakis et al., 2023; Sheu & Choi, 2022; Wang et al., 2022). By digitization adoption, ATP may acquire a competitive edge. Indeed, according to Orkestra (2023), in the next two to three years, Supply-chain 4.0 has the potential for a reduction in operational costs, lost sales, and inventories up to 30%, 75%, and 75% lower, respectively, and a significant improvement in supply chain agility.

Additionally, the study advises promoting correct working postures through ergonomics and motion studies. A deeper analysis should be conducted to learn more about the frequency and forecasting of future demands from primary ATP consumers. Better visions of the demand tendency would affect the way of management and the final warehouse layout, which could be effectively used and conducted over a long time, contributing to ATP's sustainable competitiveness across economic, social, and environmental dimensions.

10 CONCLUSIONS AND FUTURE RESEARCH

10.1 CONCLUSIONS

An approach to TSP heuristic algorithm solving by LINGO software has been conducted in the ATP warehouse. The goal is to minimize the total traveled distances during the order picking within the warehouse. This leads to respective decisions in the storage layout policy, adjusting from randomized storage to dedicated storage.

In detail, the activity-to-space ratios of each SKU in the current layout are computed to define the respective suitable storage locations to ensure the maximum throughput in the dedicated storage is prioritized. The distances of each bay are determined by calculating the rectilinear distances among the docks and the centroid of each bay currently being considered. Each scenario has a different layout and specific amounts of docks are used in the warehouse, the distances corresponding to each method are computed. Results gained by running the LINGO solver collected in each scenario; the percentage of total utilization compared to the other maps as a paired comparison, are computed to produce the best map with the shortest traveling path.

Specifically, through practical testing and program running, the total time traveling and expected distances traveled are massively decreased with Map 2 and Map 1 by redistributing the storage in a more reasonably considered, logical calculation, and reorganizing the warehouse layout. From a managerial standpoint, implementing the optimal Map 2 strategy in ATP is crucial for optimizing warehouse management operations. In addition to achieving customer satisfaction and meeting their specific requirements, this approach enables the ATP company to gain a competitive advantage, leading to enhanced efficiency and effectiveness in their business operations. In summary, the study satisfies established objectives in rearranging the current layout and optimizing picking traveled distance to make insightful suggestions to ATP management for better organizational performance.

10.2 LIMITATIONS AND FURTHER RESEARCH

This paper worked on the typical issues of order-picking design (i.e., warehouse layout, picking process, policies, etc.) in an application context. However, the authors encountered specific problems during this study, such as KPIs measured, problem constraints, and parameters described as the trends in order picking (Casella et al., 2023). For example, the study has not fully considered such realistic constraints that are ‘visible’ in real-life such as obsolete inventory, labor costs or overtime constraints in the human factors, or resources and safety constraints in the system aspects (Vanheusden et al., 2022). Moreover, the layouts and storage are proposed based on given data on stable demands at certain times. Therefore, related calculations might not work effectively in relation to remarkable changes in the future demands of ATP’s customers and distributors. In terms of increased technology along with sustainable competitiveness, investigation of more factors are needed, such as culture (Lazar & Chithra, 2022). In terms of mathematical models and algorithms, other powerful composite heuristics and programming languages should be developed to find optimal solutions, such as genetic algorithms and Python.

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Appendices

Appendix *A* – The current warehouse of ATP.

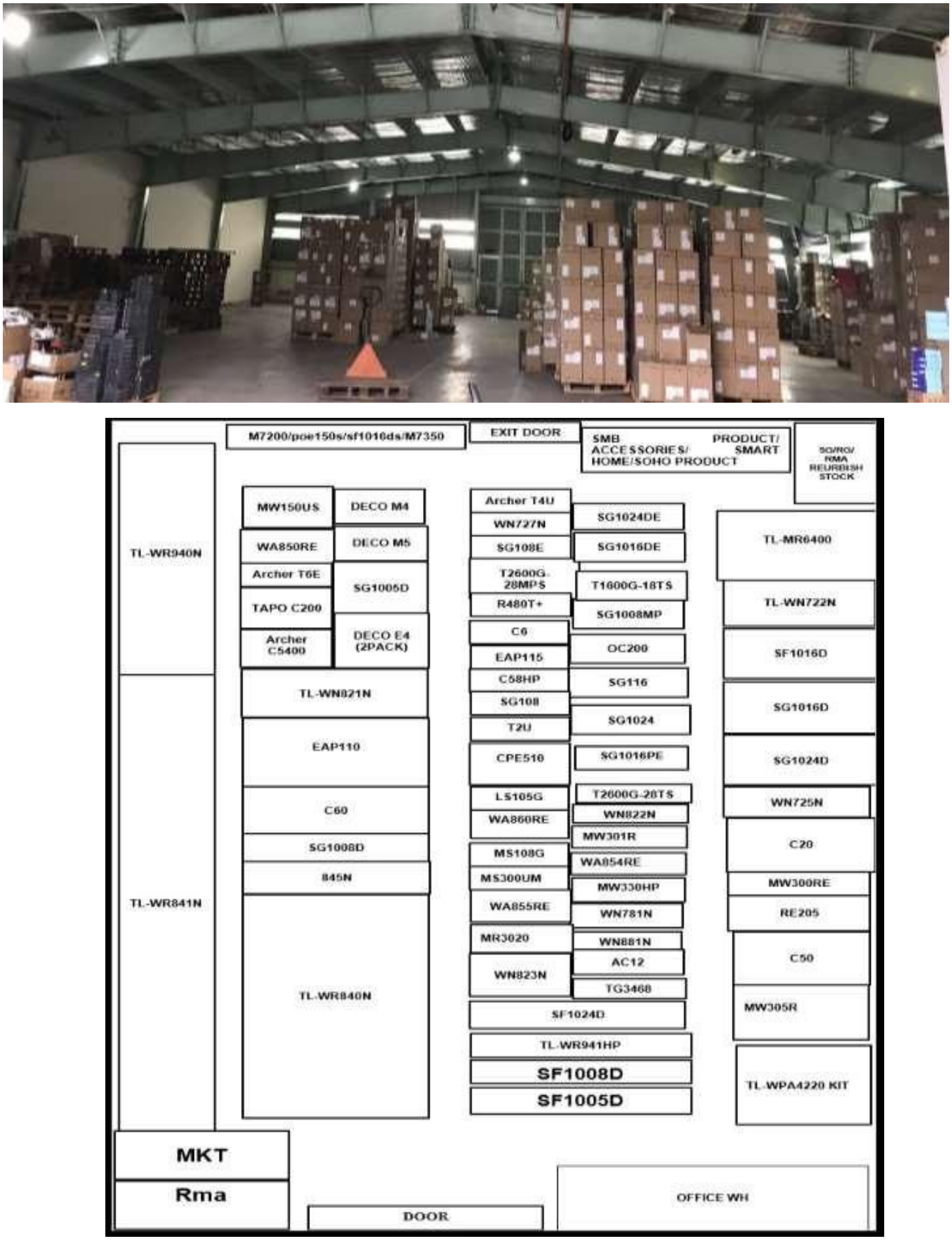
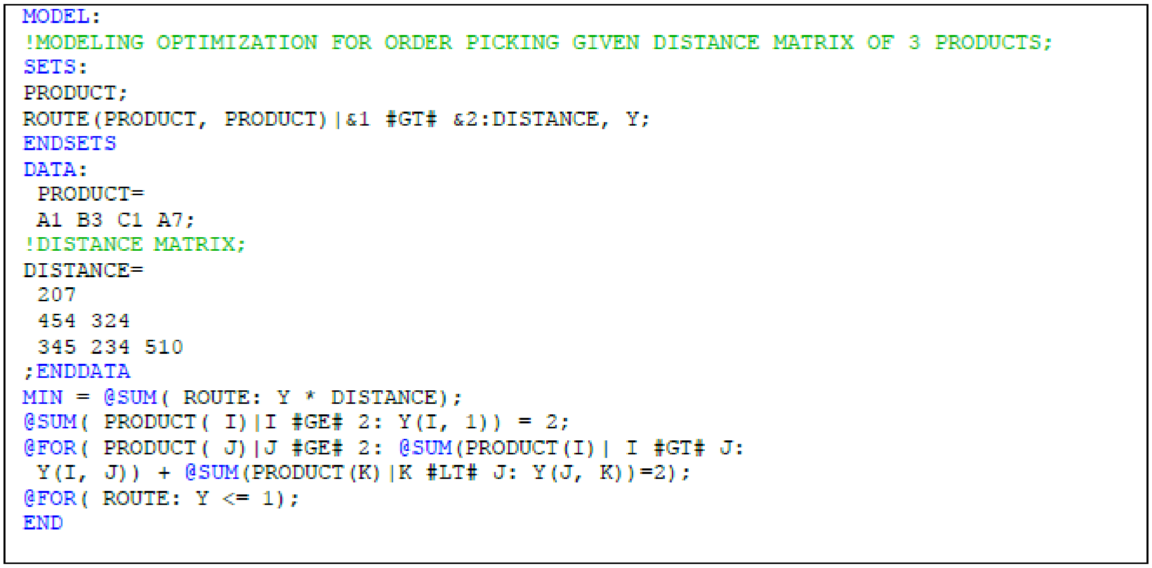


Figure: Current warehouse since March 2011 (Map 0)

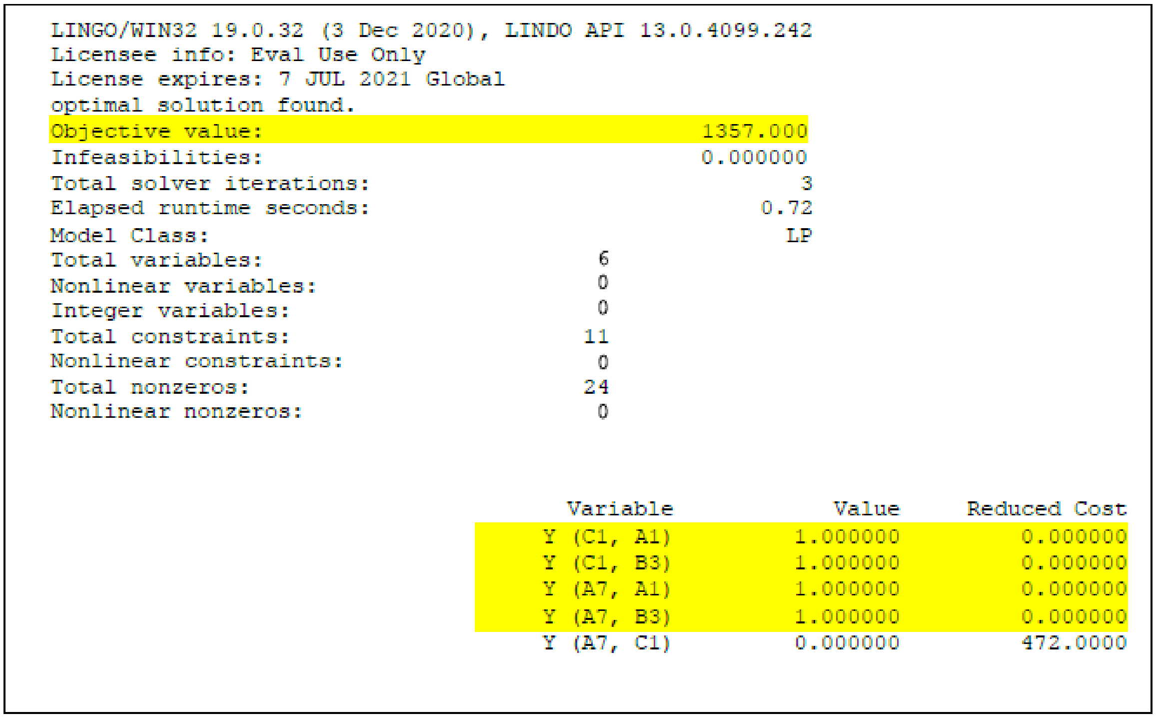
Appendix *B* – Random code for 44 SKUs.

	Random code	Item model
1	A1	TL-WN722N
2	A2	TL-SF1005D
3	A3	TL-SF1008D
4	A4	TL-WN725N
5	A5	TL-WR840N
6	A6	Archer C20
7	A7	TL-WR841N
8	B1	TL-WN781ND
9	B2	TL-WA850RE
10	B3	TL-WR845N
11	B4	TL-SG1008D
12	B5	TL-SG1005D
13	B6	Archer C60
14	B7	M7350
15	B8	TL-SG1016D
16	B9	TL-SF1016D
17	B10	Archer C6
18	B11	TL-WN822N
19	B12	Archer C50
20	C2	M7200
21	C10	TL-SG1024D
22	C1	Deco M5(3-pack)
23	C3	TL-WN821N
24	C4	TL-MR6400
25	C5	Archer T2U Nano
26	C6	TL-WR940N
27	C7	Deco M4(2-pack)
28	C8	LS105G
29	C9	TL-WA860RE
30	C11	RE205
31	C12	Archer C58HP
32	C13	Deco E4(2-pack)
33	C14	EAP110
34	C15	TL-WA855RE
35	C16	TL-SF1024D
36	C17	Archer T4U
37	C18	RE200
38	C19	TL-WPA4220 KIT
39	C20	MW150US
40	C21	TL-WN727N
41	C22	Archer T6E
42	C23	MW305R
43	C24	Archer C5400
44	C25	TL-R480T+

Appendix C – An illustration for algorithm running.



```
MODEL:
!MODELING OPTIMIZATION FOR ORDER PICKING GIVEN DISTANCE MATRIX OF 3 PRODUCTS;
SETS:
PRODUCT;
ROUTE(PRODUCT, PRODUCT)|&1 #GT# &2:DISTANCE, Y;
ENDSETS
DATA:
 PRODUCT=
 A1 B3 C1 A7;
!DISTANCE MATRIX;
DISTANCE=
 207
 454 324
 345 234 510
;ENDDATA
MIN = @SUM( ROUTE: Y * DISTANCE);
@SUM( PRODUCT( I)|I #GE# 2: Y(I, 1)) = 2;
@FOR( PRODUCT( J)|J #GE# 2: @SUM(PRODUCT(I)| I #GT# J:
 Y(I, J)) + @SUM(PRODUCT(K)|K #LT# J: Y(J, K))=2);
@FOR( ROUTE: Y <= 1);
END
```



```
LINGO/WIN32 19.0.32 (3 Dec 2020), LINDO API 13.0.4099.242
Licensee info: Eval Use Only
License expires: 7 JUL 2021 Global
optimal solution found.
Objective value:                                    1357.000
Infeasibilities:                                    0.000000
Total solver iterations:                                   3
Elapsed runtime seconds:                                0.72
Model Class:                                              LP
Total variables:                      6
Nonlinear variables:                  0
Integer variables:                    0
Total constraints:                   11
Nonlinear constraints:                0
Total nonzeros:                      24
Nonlinear nonzeros:                   0


                                    Variable           Value        Reduced Cost
                                   Y (C1, A1)        1.000000            0.000000
                                   Y (C1, B3)        1.000000            0.000000
                                   Y (A7, A1)        1.000000            0.000000
                                   Y (A7, B3)        1.000000            0.000000
                                   Y (A7, C1)        0.000000            472.0000
```

Appendix *D* – Activity-to-space calculation

No.	Random code	Activity (T_j) (loads/month)	Bays required (S_j)	T_j/S_j
1	A1	9670	10	967.0
2	A2	10302	16	643.9
3	A3	5488	20	274.4
4	A4	12905	6	2,150.8
5	A5	10456	4	2,614.0
6	A6	6671	3	2,223.7
7	A7	11579	3	3,859.7
8	B1	2284	1	2,284.0
9	B2	4774	2	2,387.0
10	B3	1060	1	1,060.0
11	B4	3820	2	1,910.0
12	B5	1947	2	973.5
13	B6	2233	1	2,233.0
14	B7	586	1	586.0
15	B8	3054	1	3,054.0
16	B9	2923	2	1,461.5
17	B10	270	1	270.0
18	B11	724	1	724.0
19	B12	3717	1	3,717.0
20	C2	154	1	154.0
21	C10	1169	1	1,169.0
22	C1	310	1	2243.0
23	C3	1449		
24	C4	173		
25	C5	157		
26	C6	154		
27	C7	43	1	662.0
28	C8	216		
29	C9	243		
30	C11	3		
31	C12	157		
32	C13	85	1	2056.0
33	C14	207		
34	C15	397		
35	C16	1064		
36	C17	179		
37	C18	124		
38	C19	65	1	717.0
39	C20	453		
40	C21	76		
41	C22	123		
42	C23	3633	1	3690.0
43	C24	6		
44	C25	51		

Appendix E - Expected distance travel of Map 1

Bay$_k$	p_1	d_{1k} (m)	f_k_EDT (m)	Bay$_k$	d_{1k} (m)	f_k_EDT (m)
1	1	18	**18**	44	36	**36**
2	1	20	**20**	45	16	**16**
3	1	22	**22**	46	18	**18**
4	1	24	**24**	47	20	**20**
5	1	26	**26**	48	22	**22**
6	1	28	**28**	49	24	**24**
7	1	30	**30**	50	26	**26**
8	1	32	**32**	51	28	**28**
9	1	34	**34**	52	30	**30**
10	1	36	**36**	53	32	**32**
11	1	38	**38**	54	34	**34**
12	1	40	**40**	55	36	**36**
13	1	18	**18**	56	38	**38**
14	1	20	**20**	57	24	**24**
15	1	22	**22**	58	26	**26**
16	1	24	**24**	59	28	**28**
17	1	26	**26**	60	30	**30**
18	1	28	**28**	61	32	**32**
19	1	30	**30**	62	34	**34**
20	1	32	**32**	63	36	**36**
21	1	34	**34**	64	38	**38**
22	1	36	**36**	65	40	**40**
23	1	16	**16**	66	42	**42**
24	1	18	**18**	67	26	**26**
25	1	20	**20**	68	28	**28**
26	1	22	**22**	69	30	**30**
27	1	24	**24**	70	32	**32**
28	1	26	**26**	71	34	**34**
29	1	28	**28**	72	36	**36**
30	1	30	**30**	73	38	**38**
31	1	32	**32**	74	40	**40**
32	1	34	**34**	75	42	**42**
33	1	14	**14**	76	44	**44**
34	1	16	**16**	77	26	**26**
35	1	18	**18**	78	28	**28**
36	1	20	**20**	79	30	**30**
37	1	22	**22**	80	32	**32**
38	1	24	**24**	81	34	**34**
39	1	26	**26**	82	36	**36**
40	1	28	**28**	83	38	**38**
41	1	30	**30**	84	40	**40**
42	1	32	**32**	85	42	**42**

43	1	34	**34**			

Appendix *F* – Expected distance travel of Map 2

Bay$_k$	p_1	p_2	d_{1k}	d_{2k}	**f_k_EDT (m)**	Bay$_k$	d_{1k}	d_{2k}	**f_k_EDT (m)**
1	0.5	0.5	14	24	**19**	44	20	24	**22**
2	0.5	0.5	16	26	**21**	45	22	26	**24**
3	0.5	0.5	18	28	**23**	46	24	28	**26**
4	0.5	0.5	20	30	**25**	47	26	30	**28**
5	0.5	0.5	22	32	**27**	48	28	32	**30**
6	0.5	0.5	24	34	**29**	49	30	34	**32**
7	0.5	0.5	26	36	**31**	50	32	36	**34**
8	0.5	0.5	28	38	**33**	51	34	38	**36**
9	0.5	0.5	30	40	**35**	52	36	40	**38**
10	0.5	0.5	32	42	**37**	53	16	12	**14**
11	0.5	0.5	34	44	**39**	54	18	14	**16**
12	0.5	0.5	36	46	**41**	55	20	16	**18**
13	0.5	0.5	38	48	**43**	56	22	18	**20**
14	0.5	0.5	12	22	**17**	57	24	20	**22**
15	0.5	0.5	14	24	**19**	58	26	22	**24**
16	0.5	0.5	16	26	**21**	59	28	24	**26**
17	0.5	0.5	18	28	**23**	60	30	26	**28**
18	0.5	0.5	20	30	**25**	61	32	28	**30**
19	0.5	0.5	22	32	**27**	62	34	30	**32**
20	0.5	0.5	24	34	**29**	63	36	32	**34**
21	0.5	0.5	26	36	**31**	64	38	34	**36**
22	0.5	0.5	28	38	**33**	65	40	36	**38**
23	0.5	0.5	30	40	**35**	66	18	10	**14**
24	0.5	0.5	32	42	**37**	67	20	12	**16**
25	0.5	0.5	34	44	**39**	68	22	14	**18**
26	0.5	0.5	36	46	**41**	69	24	16	**20**
27	0.5	0.5	10	18	**14**	70	26	18	**22**
28	0.5	0.5	12	20	**16**	71	28	20	**24**
29	0.5	0.5	14	22	**18**	72	30	22	**26**
30	0.5	0.5	16	24	**20**	73	32	24	**28**
31	0.5	0.5	18	26	**22**	74	34	26	**30**
32	0.5	0.5	20	28	**24**	75	36	28	**32**
33	0.5	0.5	22	30	**26**	76	38	30	**34**
34	0.5	0.5	24	32	**28**	77	40	32	**36**
35	0.5	0.5	26	34	**30**	78	42	34	**38**
36	0.5	0.5	28	36	**32**	79	34	24	**29**
37	0.5	0.5	30	38	**34**	80	36	26	**31**

38	0.5	0.5	32	40	**36**	81	38	28	**33**
39	0.5	0.5	34	42	**38**	82	40	30	**35**
40	0.5	0.5	12	16	**14**	83	42	32	**37**
41	0.5	0.5	14	18	**16**	84	44	34	**39**
42	0.5	0.5	16	20	**18**	85	46	36	**41**
43	0.5	0.5	18	22	**20**				