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Pallet Loading Optimization Considering Storage Time and Relative Humidity

Najat Almasarwah[1], Esraa Abdelall[2], Gursel Suer[3†], Gokhan Egilmez[4],
Manjeet Singh[5], Saleem Ramadan[6]

[1]*Department of Industrial Systems Engineering, Mutah University (Jordan)*
[2]*Industrial Engineering Department, Jordan University of Science and Technology (Jordan)*
[3]*Industrial and Systems Engineering, Ohio University (USA)*
[4]*Department of Mechanical and Industrial Engineering, University of New Haven (United States)*
[5]*Solutions Design, DHL Supply Chain (United States)*
[6]*Department of Industrial and Systems Engineering, Youngstown State University (United States)*

najat.eid@mutah.edu.jo, Esabdulal@just.edu.jo, Suer@ohio.edu, Gegilmez@NewHaven.edu,
Manjeet.singh3@dhl.com, szramadan@ysu.edu

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Abstract:

Purpose: This paper studies a 3-dimensional pallet loading problem considering interlock stacking pattern, box dimensions, humidity, and storage time, where overlapping and overhanging are not allowed. Despite the importance of this problem in the literature, our work provides the first method that considers the environmental conditions such as 1) storage time and 2) humidity, and their tremendous impacts on the strength of the boxes, as has been observed widely in the DHL supply chain.

Design/methodology/approach: This paper proposes a two-phase heuristic algorithm to solve a 3-dimensional pallet loading problem under real conditions (relative humidity, and storage time) considering interlock stacking patterns, where overlapping and overhanging are not allowed. In phase 1, the horizontal layer configuration is determined by block techniques. Three types of horizontal layers are created based on box dimensions perpendicular to the base. In phase 2, a novel mathematical model is propounded to improve the pallet volume utilization, and stability considering the pallet's maximum allowable height and weight, and the dynamic compression strength of boxes. The dynamic compression strength of boxes is calculated by the modified McKee formula. Two performance measures, pallet volume utilization, and stability (load height) are utilized to evaluate the performance of the proposed heuristic algorithm in real-world instances (DHL Supply Chain).

Findings: The results illustrated that the dynamic compression strength of boxes decreases as the relative humidity and storage time increase. The load height changes dynamically along with box dimensions, box alignment, direction, relative humidity, and storage time. Increasing relative humidity and storage time and applying an interlock stacking pattern reduce the pallet utilization, however, enhance the pallet stability. Finally, the proposed heuristic algorithm's efficacy increases as the identical box dimensions' heterogeneity increases.

Originality/value: It is believed in the supply chain where these characteristics are observed, the implementation of the heuristic algorithm will help them improve the pallet volume utilization and stability.

Keywords: pallet loading problem, two-phase heuristic algorithm, real conditions, dynamic compression strength, interlock stacking patterns

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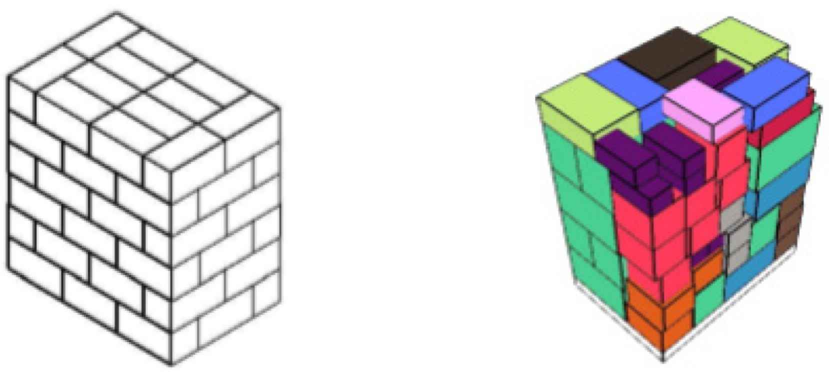
1. Introduction

Pallet loading is crucial for supply chain efficiency as it affects operating cost and customer satisfaction. In literature, the pallet loading problem is handled by orthogonally packing boxes with any given rectangular shaped onto a rectangular pallet of fixed and known dimensions to improve volume utilization and stability of pallets (Martins & Dell, 2008). Typically, the pallet loading problem is divided into two groups considering the boxes' size (Singh, Almasarwah & Süer, 2019), as depicted in Figure 1, the manufacturer's pallet loading problem and the distributor s pallet loading problem. It is also called a uniform pallet loading problem characterized by having identical sizes of boxes (homogeneous boxes) unlike the distributor s pallet loading problem or mixed pallet loading problem where the sizes of boxes are non-identical (weakly or strongly heterogeneous) (Gonçalves & Resende, 2012; Mungwattana, Piyachayawat & Janssens, 2022). In this paper, the uniform pallet loading problem is covered.



a) Uniform Pallet Loading Problem b) Mixed Pallet Loading Problem (Schuster, Bormann, Steidl, Reynolds-Haertle & Stilman, 2010)

Figure 1. Two Groups of the Pallet Loading Problem

In recent years, several solution approaches to the pallet loading problem have been developed. These approaches were either exact or heuristic algorithm methods. The exact methods, mostly based on the mathematical models, (Alonso, Alvarez-Valdes, Iori, Parreño & Tamarit, 2017; Kocjan & Holmström, 2010), are practical for moderate and small problems. The heuristics have been also used to obtain the optimal or near-optimal solution in a reasonable amount of time (Dowsland, 1987). Besides these, artificial intelligence was also used due to its applicability to the NP-hard problem (Aylak, İnce, Oral, Süer, Almasarwah, Singh et al., 2021). Further, different types of methods were utilized such as a Coloured Petri Net model (Piera, Zuñiga & Mújica, 2009), heuristic algorithms (Birgin, Morabito & Nishihara, 2005; Singh et al., 2019; Burduk, Balashov, Lapczyńska & Musial, 2022; Ko & Hsieh, 2023), or metaheuristic algorithms, such as genetic algorithms (Lau, Chan, Tsui, Ho & Choy, 2009; Ancora, Palli & Melchiorri, 2022), simulated annealing (Hu, Zuo & Sun, 2022) and tabu search (Pureza & Morabito, 2006). Several variants of the above heuristics and metaheuristics, as well as hybrid approaches, enabled researchers to consider different performance measures, such as pallet volume utilization, profit, and pallet stability (Ren, Choi, Lee & Lin, 2020). For example, Lau et al. (2009) developed a hybrid approach, derived from heuristic and genetic algorithms, to optimize profit in pallet loading operations, where the results illustrated the ability of the hybrid approach to maximize the profit. Aljuhani and Papageorgiou (2021) developed a mixed integer linear programming model to generate layouts of the horizontal layers to maximize the pallet utilization percentage and reduce the complexity of the loading process. The findings illustrated the superiority of the proposed approach compared to the literature in terms of maximizing pallet utilization. Calzavara, Iori, Locatelli, Moreira and Silveira (2021) used a mathematical model and heuristic algorithms to load boxes onto the pallets. Their results illustrated the effectiveness of the proposed approaches to improve pallet utilization. Gunawardena, Wijayanayake and Kavirathna (2021) utilized a two-phase algorithm to solve the pallet loading problem. The results demonstrated the ability of the proposed algorithm to improve pallet area utilization. Zacchei, Tadeu, Almeida, Esteves, Santos and Silva (2022) studied the possibility of using a steel pallet instead of a wood pallet. The experimental tests showed that the new propounded pallet performance is better that its wood.

Despite all these efforts, studies of the pallet loading problem considering humidity and storage time are very limited. For instance, a study by Malasri, Pourhashemi, Brown, Harvey, Moats, Godwin et al. (2013) explained the effect of temperature and humidity on the strength of softwood pallets. Their study relied on the compression strength of the pallet to define its performance. The results revealed an inverse relationship between the compression strength of softwood pallets and temperature. Another study by Fadiji, Coetzee and Opara (2016) illustrated the negative effect of humidity on compression strength, where the compression strength of paperboard packages decreases as humidity increases. The authors used the Lansmont compression tester-squeezer in their experiment besides using the finite element modeling to analyze the results. Novas, Ramello and Rodríguez (2020), on the other hand, showed that the dynamic compression strength of boxes affected by relative humidity, loading stacking patterns, and storage time. Sawicki and Sawicka (2023) propounded a binary programming model to maximize the space utilization in the distribution center. The results illustrated that the space utilization increases as the stacked palletized is utilized.

This study arose from a research initiative at DHL Supply Chain. DHL Supply Chain is researching the best methods to load boxes onto a pallet considering humidity, interlock stacking pattern, and storage time. Change in humidity was stated to affect the stability, the strength of the pallet, and the box's mechanical strength over time (Berry, Ambaw, Defraeye, Coetzee & Opara, 2019). The pallet stability depends on the number of horizontal layers per pallet, and the layout pattern of boxes per horizontal layer, this represents a 3-dimensional manufacturer's PLP. To the best of our knowledge, no work in the literature tried to solve a 3-dimensional pallet loading problem, where the identical boxes are loaded onto the pallet with mixed types of the horizontal layer considering the relative humidity, interlock stacking pattern, and storage time and their impact on the dynamic compression strength of the box as it is discussed in this paper. A two-phase algorithm is proposed to solve the aforementioned 3-dimension PLP taking into consideration two performance measures: the pallet volume utilization, and pallet stability. In this first phase, the number of identical boxes per horizontal layer and the corresponding box loading layout or pattern are determined. In the second phase, the maximum number of boxes per pallet is calculated using a mixed integer linear mathematical model.

The remaining parts of this paper are as follows: Section 2 explains the proposed methodology. Section 3 shows the experimentation and results. Finally, in section 4, the overall conclusion and future research directions are stated.

2. Methodology

In this paper, a two-phase heuristic algorithm is propounded to tackle the uniform pallet loading problem. The first phase, horizontal layer configurations, determines the number of boxes loaded onto the three types of horizontal layers. The second phase maximizes the total number of boxes loaded onto a pallet considering three parameters, the maximum allowable pallet height (H_{max}), the maximum allowable weight (M_{max}) and the dynamic compression strength of the box. The pallet volume utilization, load height, and a pallet stacked run illustrate the efficacy of the proposed two-phase heuristic algorithm. Figure 2 illustrates an overview of the methodology used.

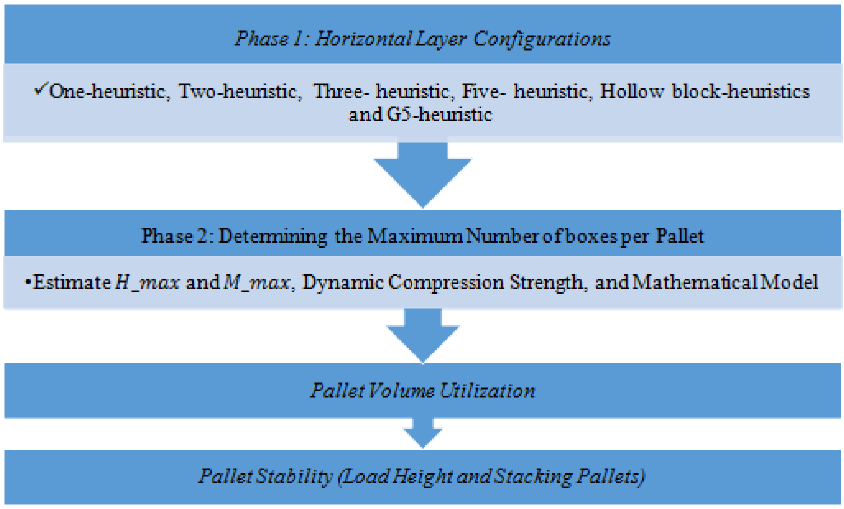
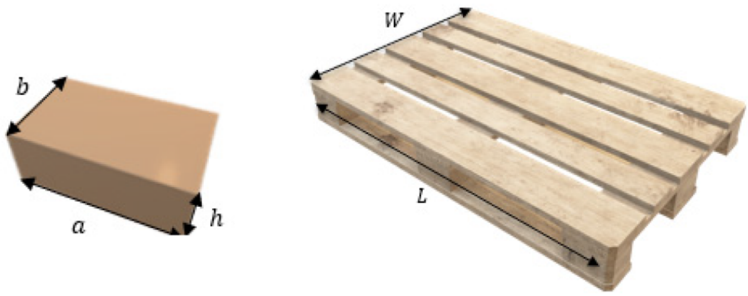


Figure 2. An Overview of Methodology Used

2.1. Phase 1: Horizontal Layer Configurations

Once the ratio between the pallet area and the box area from the top view is less than 101 (*i.e.*, Martins & Dell, 2008), one at least of the following six heuristics, one-, two-, three-, five-, hollow block-heuristics, and the G5-heuristic, might yield the maximum number of boxes per horizontal layer (Prasad & Krishnakumar, 2021). Let (a, b, h, w) and ($L, W, H_{max}, M, M_{max}$) be an instance of box and pallet dimensions studied in this paper, respectively (Figure 3), where a is the box length, b is the box width, h is the box height, w is the box weight; L is the pallet length, W is the pallet width, and M is the pallet weight.



a) Box's Dimensions b) Pallet's Dimensions

Figure 3. Box and Pallet Dimensions

Assuming that (15.00 in, 13.875 in, 11.750 in, 28.911 lb) and (45.00 in, 41.60 in, 39.7 in, 50.00 lb, 780.597 lb) are the box and pallet dimensions. Then, the maximum number of boxes per three types of horizontal layers is obtained by a one-block heuristic. The results reported in Table 1 illustrate that the optimal number of boxes per horizontal layer is obtained by the two horizontal layers (*LWa* and *LWb*) based on the results of the simulation software (Microsoft Visual Basic).

Horizontal Layer Type	Dimension Perpendicular to Base	Boxes/Horizontal Layer (z_i)
LWa	*a*	9
LWb	*b*	9
LWh	*h*	6

Table 1. The Maximum Number of Boxes per Pallet.

2.2. Phase 2: Determining the Maximum Number of Boxes per Pallet

The number of boxes and the type of horizontal layers per pallet are determined in this phase using a novel linear mathematical model considering three parameters, (a) H_{max}, (b) M_{max}, and (c) dynamic compression strength considering relative humidity, interlock stacking pattern, dimension of the box, and storage time.

2.2.1. H_{max} and M_{max}

The H_{max} is determined either based on the storage on the pallet within the warehouse, i.e., racks, floor, etc., or based on the transportation constraints, i.e., trailer internal height, number of horizontal layers loaded, etc. Furthermore, the total weight of the pallet should not be more than M_{max}. This is important for several reasons. First, if there is no height limit, the number of boxes per pallet will be determined based on the M_{max} per pallet. Second, the total weight on the boxes per pallet when loading on the shelves or the trailers should not be more than the maximum weight capacity to avoid the pallets, the shelves, or the trailers damage (Singh et al., 2019).

2.2.2. Dynamic Compression Strength

Pallet Static compression strength is a theoretical value under lab conditions (73°±2°F and 50%±2% Relative humidity), (Aylak et al., 2021). The static compression strength can be calculated using the McKee formula as given in Equation 1 (McKee, Gander & Wachuta, 1963). ECT is the Carton Edge Crush Test. CAL is the caliper of the corrugated board, PER is the box perimeter from the top view. The compression strength of a box under real conditions is called dynamic compression strength (Frank, 2014). It is computed by multiplying factors by the static compression strength, as given in Equation 2. F_o is the orientation coefficient from strength, F_T is the storage time coefficient, F_I is the interlock coefficient, F_H is the relative humidity coefficient, and F_G is the pallet shape coefficient (Table 2). For example, F_H is 0.9, when the relative humidity is between 55% – 65%, and F_T is 0.6, when the storage time is between 11 – 30 days, and *so on*. Clearly, the dynamic compression strength of a box decreases as the relative humidity and storage time increase.

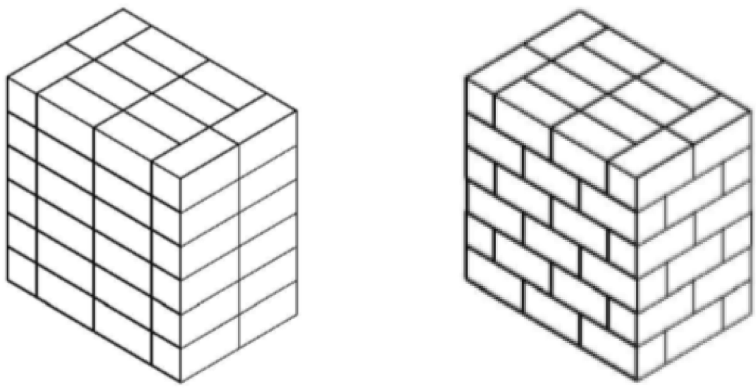
$$\text{Static Compression Strength } (S_S) = 5.874 * \text{ECT} * \text{CAL}^{0.508} * \text{PER}^{0.492} \tag{1}$$

$$\text{Dynamic Compression Strength } (S_D) = S_S * F_T * F_H * F_G * F_o * F_I \tag{2}$$

Storage Time (Days)	F_T	%Relative Humidity	F_H	Pallet Surface Gapped	F_G	Interlock	F_I	Perpendicular Dimension to Base	F_o
0	1.00	0~45	1.1	Yes	0.92	Yes	0.60	1st Shortest Dimension of Box	1.00
1~3	0.70	45~55	1.00	No	1.00	No	1.00	2nd Shortest Dimension of Box	0.90
4~10	0.65	55~65	0.90					Longest Dimension of Box	0.80
11~30	0.60	65~75	0.80						
31~90	0.55	75~85	0.70						
91~120	0.50	85~100	0.50						
121~300	0.45								

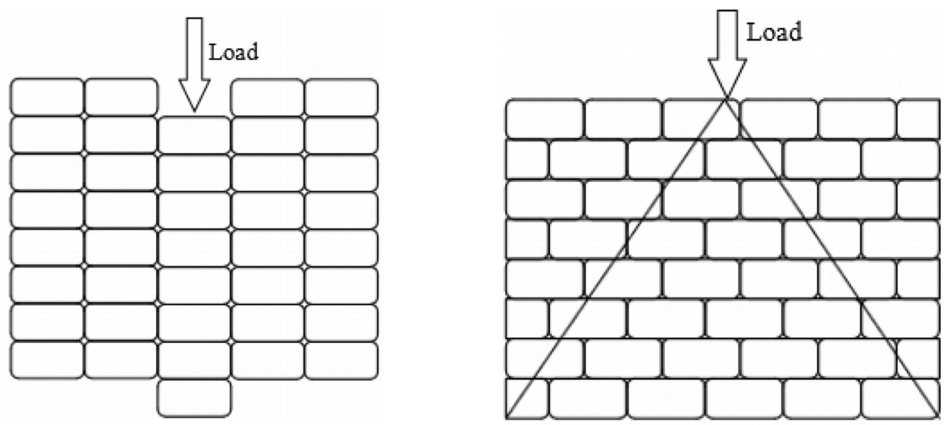
Table 2. Dynamic Strength Factors (Cape Pack, 2012).

Considering the types of horizontal layers used to load boxes onto the pallet, two patterns of stacking appear. The first pattern is columnar stacking, where all horizontal layers in the pallet have the same layout (Figure 4a). In this pattern, the boxes are loaded onto horizontal layers, wherein the boxes are edge-to-edge and corner-to-corner. Thus, the strength of the boxes is high, while the pallet stability is low due to the load distribution (Singh, Singh & Saha, 2011), as shown in Figure 5a. Two third (2/3) of potential compression exists in the vertical corners and edges. In this regard, the boxes should be seamed edge-to-edge and corner-to-corner for the greatest stacking strength (Balakirsky, Kramer & Proctor, 2010). The second pattern is the interlock stacking pattern. This pattern appears in the pallet when different types of horizontal layers are utilized, or when the altered layouts of the same horizontal layer are used (Figure 4b). Thus, if the same pattern is used for every horizontal layer on a given pallet, the layer should be rotated 180 degrees to avoid the columnar stacking pattern. Thus, the edge-to-edge and corner-to-corner are not matched, as given in Figure 5b. The interlocking pattern reduces the dynamic compression strength of boxes, while it improves the pallet stability compared with the columnar stacking patterns (Molina, Horvath & White, 2018). Based on the first law of motion (Lin, Kim, Kim & Jun, 2011), the pallet moves when the forklift or trailer applies force on the base. The top horizontal layer does not want to move, but the motion transfers by friction up through the boxes to the top layer. If this transfers too slowly, the boxes become out of balance and fall over. When all boxes are interlocked the friction between the boxes makes the whole pallet act as a single integrated unit. Using the interlock stacking pattern on the horizontal layers increases the friction between the horizontal layers; therefore, the possibility of the pallet falling over decreases. Thus, the interlock coefficient is important as it improves the stability and stiffness of the pallet, but at the same time, it reduces the dynamic strength of boxes by up to 60% (Table 2).



a) Columnar Stacking Pattern b) Interlock Stacking Pattern

Figure 4. Pallet Loading Stacking Patterns



a) Load Distribution in the Columnar Stacking Pattern (*Unbounded Wall*) b) Load Distribution in the Interlocking Stacking Pattern *(Bounded Wall)*

Figure 5. Load Distribution in the Loading Stacking Patterns

2.2.3. Mathematical Model

The objective function of the proposed mathematical model is to maximize the number of boxes per pallet (Equation 3). Equation 4 calculates the number of boxes per pallet. Equation 5 ensures that the total heights of horizontal layers loaded onto pallets don't exceed the H_{max}. Equation 6 guarantees that the number of horizontal layers does not exceed the number of horizontal layers obtained by the maximum dynamic compression strength of the *bottom box* (the boxes loaded onto a bottom layer). Equation 7 defines the number of boxes based on the M_{max}. Equation 8 determines the number of horizontal layers loaded onto a pallet based on the dynamic compression strength of the bottom box. It is worth mentioning that in case more than one type of horizontal layer is used to load boxes onto the pallet, a horizontal layer with maximum dynamic strength is being a bottom horizontal layer of a pallet. Equation 9 computes the dynamic compression strength of a box considering the relative humidity, interlock, storage time, and the box perimeter from the top view of a box. Equation 10 estimates the maximum dynamic compression strength of the box. Equation 11 defines the type(s) of horizontal layers used to load the boxes. Finally, Equation 12 restricts the types of horizontal layers loaded onto a pallet.

Objective Function

$$Maximize \quad NB \tag{3}$$

Subject to

$$NB = \sum_{i \in k} z_i * Y_i \qquad k \in a, b, h \tag{4}$$

$$\sum_{i \in k} d_i * Y_i \leq H_{max} \qquad k \in a, b, h \tag{5}$$

$$\sum_{i \in k} Y_i \leq N_{S_{DD}} \qquad k \in a, b, h \tag{6}$$

$$w * NB \leq M_{max} \tag{7}$$

$$N_{S_{DD}} = \frac{S_{DD}}{m} \tag{8}$$

$$S_{D_i} = 5.874 * ECT * CAL^{0.508} * I_i * PER_i^{0.492} * F_T * F_G * F_H * F_I * F_{o_i} \qquad i \in a, b, h \tag{9}$$

$$S_{DD} = \max(S_{D_a}, S_{D_b}, S_{D_h}) \tag{10}$$

$$I_i = \begin{cases} 1 & Y_i \geq 1 \\ 0 & Y_i = 0 \end{cases} \qquad i \in a, b, h \tag{11}$$

$$\sum_{i \in k} I_i \leq NofR \qquad k \in a, b, h \tag{12}$$

$$S_D, N_{S_{DD}} \quad \text{Real Number} \tag{13}$$

Indices:

i	The Dimension of Box index

Parameters:

k	The Length (a), the Width (b) and the Height (h) of Box.
PER_i	Box perimeter from top view when dimension i is vertical to the base.
d_i	The height of the horizontal layer when dimension i of the box is perpendicular to the base.
F_{oi}	Orientation coefficient for box strength considering dimension i is perpendicular to the base.
z_i	Boxes/Horizontal Layer with dimension i of a box is perpendicular to the base, as given in Table 1.
$NofR$	The allowed number of horizontal layer(s) per pallet.

Decision Variables:

Y_i The number of horizontal layers is used when dimension *i* is perpendicular to the base (Integer Number).
S_{DD} Maximum Dynamic Compression Strength of Box.
I_i 1 if horizontal layer with dimension *i* perpendicular to base is used to load boxes onto pallet; 0 otherwise.
S_{Di} Dynamic Compresion Strength when dimension *i* (*a, b,* & *h*) is perpendicular to base.
$N_{S_{DD}}$ The number of horizontal layers based on the maximum dynamic compression strength.
NB The Number of Boxes per pallet.

The mathematical model is solved using the CPLEX 12.8 software, and the relative humidity is set at 70%, the storage time equals 30 days, the caliper is 0.16, *NofR* is 3, and *ECT* is 26. The results explain that the maximum number of boxes per pallet is 24. It acquires when the two horizontal layers of type *LWb* and one horizontal layer of type *LWh* are used. The dynamic compression strength of the box in the first (*LWb*) and the second (*LWh*) horizontal layers is 354.31 and 398.59, respectively. Thus, the horizontal layer type *LWh* is the bottom layer because it has the maximum dynamic compression strength. Meanwhile, the maximum number of boxes per pallet is 18, if only one type of horizontal layer, *LWb*, is restricted to be used. Therefore, the altered layouts for the same layer are utilized.

2.3. Pallet Volume Utilization

The pallet volume utilization is one of the performance measures used to evaluate the efficacy of the proposed two-phase heuristic algorithm in this study. Typically, volume utilization is defined as the ratio of the volume occupied by the pallet to the volume of the master pallet. Equation 14 computes the pallet utilization.

$$Pallet\ Volume\ Utilization\ (PVU) = \frac{NB * (a * b * h)}{(L * W * H_{max})} * 100\% \tag{14}$$

The *PVU* for the given example when the two types of horizontal layers are utilized is 78.97%. This means that approximately 21.03% of the total load volume on the pallet is an empty space. However, results show that the pallet stability increases, as the volume utilization increases.

2.4. Pallet Stability (Load Height and Stacking Pallets)

The load height is used in this study as a performance measure to evaluate pallet stability. The max load height is the maximum possible number of stacking pallets before the bottom boxes break. The strength of the pallet is measured by the max number of stacking pallets before breaking the bottom boxes. Two steps are utilized to calculate the load height. The first step calculates the average weight on a bottom box. The average weight on a bottom box should be equal to or less than its dynamic compression strength; otherwise, the box will break. Equation 15 calculates the average weight on the bottom box when two pallets (*AWoBL*) are stacked. Equations 16 and 17 compute the load weight ($LWoOP_1$ and $LWoOP_2$) of the bottom (the first) and top (the second) pallets (total weight of boxes at the bottom layer), respectively. Where *NoBML* is the total number of boxes at the bottom layer, and w_{ijt} is the weight of box *t* at horizontal layer number *j* when dimension *i* of a box is perpendicular to the base. *M* is the pallet weight.

$$AWoBL = \frac{LWoOP_1 + LWoOP_2}{NoBML} \tag{15}$$

$$LWoOP_1 = \sum_{i \in k} \sum_{j \in Y_{i \notin bottom\ layer}} \sum_{t \in z_i} w_{ijt} \tag{16}$$

$$LWoOP_2 = M + \sum_{i \in k} \sum_{j \in Y_i} \sum_{t \in z_i} w_{ijt} \tag{17}$$

Having determined the average weight on a bottom box, the second step estimates the Load Height based on the average of the dynamic and static compression strength of the bottom boxes using the following Equation:

$$\text{Load Height} = \text{Average}\left(\frac{S_{DD}}{AWoBL}, \frac{S_s}{AWoBL}\right) \tag{18}$$

The results reported in Table 3 illustrate that the load height when 2 pallets are stacked is 1.33. This means, stacking two pallets under the given conditions causes damage to the bottom boxes in the bottom pallet.

S_S	S_{DD}	$LWoOP_1 + LWoOP_2$	NB	LWh (Box)	$AWoBL$	LH
442.88	117.35	1264.26	24	6	210.71	1.33

Table 3. Load Height When 2 Pallets Stacked.

3. Experimentation and Results

In this section, the experimentation performed (Figure 6), and the results obtained are reported in detail.

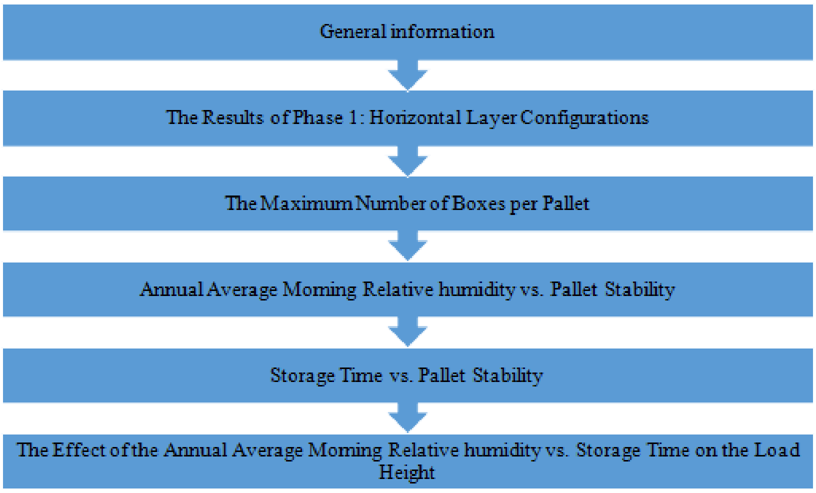


Figure 6. The hierarchical framework of experimentation and results section

3.1. General Information

A proposed two-phase heuristic algorithm has been tested by 52 real-life datasets from the DHL Supply Chain. The relative humidity and the storage time are taken into consideration since the pallets should be transferred from one place to another, where the relative humidity changes based on a place. The relative humidity is usually the highest in the morning while the lowest in the afternoon. Since higher relative humidity would reduce pallet strength, only attention needed to the highest relative humidity during the day in the storage environment.

3.2. The Results of Phase 1: Horizontal Layer Configurations

In this section, the 3-dimensional pallet loading problem is reduced to a 2-dimensional pallet loading problem. The number of boxes per horizontal layer is calculated for the 52 datasets using the developed simulation software, as given in Table 4. The running time of the proposed simulation software is less than a minute. Where the z_a, z_b and z_h represent the number of boxes per horizontal layer, when the box dimensions a, b and h are perpendicular to the base, respectively.

Dataset	Box Dimensions	Pallet Dimensions	z_a	z_b	z_h	F_{oa}	F_{ob}	F_{oh}
1	(9,5.75,8.625,5.225)	(46.8,38.5,43.125,50,888.25)	34	20	34	0.8	1	0.9
2	(9.625,7.125,10.25,6.6)	(47.75,38.5,41,50,686.4)	23	16	26	0.9	1	0.8
3	(9.375,4.812,5.375,1.46)	(46.9,38.3,43,50,455.52)	63	35	39	0.8	1	0.9

Dataset	Box Dimensions	Pallet Dimensions	z_a	z_b	z_h	F_{oa}	F_{ob}	F_{oh}
1	(9,5.75,8.625,5.225)	(46.8,38.5,43.125,50,888.25)	34	20	34	0.8	1	0.9
4	(8.5,4.378,6.752,1.227)	(47.6,38.6,40.512,50,360.738)	59	30	46	0.8	1	0.9
5	(13.062,9.812,3.25,6.788)	(45.7,39.3,42.25,50,1235.416)	56	42	13	0.8	0.9	1
6	(13,4.87,20.37,5.6)	(45.5,39,40.74,50,313.6)	16	6	28	0.9	1	0.8
7	(14.75,9.875,3.375,7.231)	(48,40,45.2,50,1041.264)	56	37	12	0.8	0.9	1
8	(13.062,9.812,3.25,6.93)	(45.7,39.3,42.25,50,1261.26)	56	42	13	0.8	0.9	1
9	(9.625,7.375,5.125,1.2)	(48,40,46,50,240)	49	36	25	0.8	0.9	1
10	(10.375,7,6.5,7.02)	(45.38,38.38,39,50,968.76)	30	23	23	0.8	0.9	1
11	(9.375,4.812,5.375,1.35)	(46.9,38.3,43,50,421.2)	63	35	39	0.8	1	0.9
12	(8.875,6.625,7.5,6.755)	(46.5,39.9,45,50,1256.43)	36	26	31	0.8	1	0.9
13	(7.5,5.252,6.535,1.32)	(47.268,38.256,39.21,50,356.4)	52	35	45	0.8	1	0.9
14	(14.688,13.813,9.375,28.295)	(43.3,40.7,37.5,50,1018.62)	12	11	6	0.8	0.9	1
15	(19,9.125,11.687,30.38)	(47.4,38.3,51.8,50,1215.2)	16	8	10	0.8	1	0.9
16	(14.437,13.562,9.062,28.7)	(43.3,40.7,41.2,50,1033.2)	13	11	8	0.8	0.9	1
17	(9,5.375,8.5,6)	(45,37.8,48.5,50,1020)	36	20	35	0.8	1	0.9
18	(9.25,8.625,7.75,3.805)	(46.2,35.1,51.5,50,456.6)	20	20	19	0.8	0.9	1
19	(10.562,10,7.562,4.015)	(41.7,40.6,50.9,50,385.44)	21	19	15	0.8	0.9	1
20	(15,13.875,11.75,28.911)	(45,41.6,39.7,50,780.597)	9	9	6	0.8	0.9	1
21	(14.437,13.562,9.062,29)	(43.3,40.7,41.2,50,1044)	13	11	8	0.8	0.9	1
22	(8.75,6.625,7.375,7.52)	(46.1,39.8,49.8,50,1398.72)	36	27	30	0.8	1	0.9
23	(8.937,6.625,7.937,7.8)	(46.7,40.1,45,50,1209)	35	25	31	0.8	1	0.9
24	(8.75,4.625,2.625,0.45)	(46.3,36.5,31.8,50,180)	137	71	40	0.8	0.9	1
25	(11.437,8.687,10.312,16.95)	(45.8,40.3,47,50,1220.4)	19	12	18	0.8	1	0.9
26	(12.937,9.937,11.312,22.91)	(48,40,50.8,50,1282.96)	16	12	14	0.8	1	0.9
27	(10.875,8.187,10.187,16.55)	(46.3,40.9,46.3,50,1390.2)	20	16	19	0.8	1	0.9
28	(19.562,9.125,7.5,18.505)	(46.9,37.8,51,50,1110.3)	25	11	8	0.8	0.9	1
29	(14.625,9.25,10.625,20.84)	(45.6,38.1,48,50,1083.68)	16	10	12	0.8	1	0.9
30	(10.875,8.187,10.187,15.33)	(46.3,40.9,46.7,50,1287.72)	20	16	19	0.8	1	0.9
31	(15.5,9.125,7.625,8.735)	(46.5,36.5,44.1,50,524.1)	24	12	12	0.8	0.9	1
32	(3.863,2.067,4.232,1.96)	(46,39.5,16.929,50,1083.68)	203	108	226	0.9	1	0.8
33	(14.438,5.688,5.75,2.05)	(45.5,37.2,45.6,50,287)	42	18	19	0.8	1	0.9
34	(8.312,6.25,7,3.41)	(48,40,48,50,879.78)	42	30	36	0.8	1	0.9
35	(8.75,7.062,5.625,4.14)	(45.8,38.7,45.3,50,811.44)	42	34	28	0.8	0.9	1
36	(9,5.375,8.5,6)	(45,37.8,48.5,50,1020)	36	20	35	0.8	1	0.9
37	(13.605,7.615,6.115,3.02)	(40.5,35.625,42.805,50,317.1)	28	15	12	0.8	0.9	1
38	(9.563,7.188,12.813,6.8)	(45.4,38.3,43.4,50,510)	15	13	24	0.9	1	0.8
39	(28.125,13.5,14.25,47.58)	(41.6,40.5,47.8,50,570.96)	7	2	3	0.8	1	0.9
40	(12.125,8.313,5.063,7.5)	(44.69,37.06,40.5,50,960)	38	26	15	0.8	0.9	1

Dataset	Box Dimensions	Pallet Dimensions	z_a	z_b	z_h	F_{oa}	F_{ob}	F_{oh}
1	(9,5.75,8.625,5.225)	(46.8,38.5,43.125,50,888.25)	34	20	34	0.8	1	0.9
41	(9.875,6.687,9.25,17.6)	(46.5,39.8,37,50,1971.2)	28	20	26	0.8	1	0.9
42	(13.605,7.615,6.115,3.02)	(40.5,35.625,42.805,50,317.1)	28	15	12	0.8	0.9	1
43	(9.37,6.299,4.882,5.5)	(47.5,38.688,43.938,50,1435.5)	58	39	30	0.8	0.9	1
44	(3,3,5,2)	(48,45,13,50,20000)	144	144	240	1	1	0.7
45	(3,3,5,2)	(48,45,29,50,20000)	144	144	240	1	1	0.7
46	(3,3,7,2)	(48,45,13,50,20000)	102	102	240	1	1	0.7
47	(8.125,7.625,4.562,1.5)	(46.1,38.6,36.496,50,360)	50	46	25	0.8	0.9	1
48	(12.25,9.125,10.375,12.414)	(48,40,46.8,50,794.496)	18	12	16	0.8	1	0.9
49	(11.875,7.75,8.25,2.3)	(47.5,39.3,46.3,50,230)	26	17	20	0.8	1	0.9
50	(10.375,6.375,8.75,2.49)	(46.3,39.9,49.3,50,336.15)	31	19	27	0.8	1	0.9
51	(10.188,5.5,6,1)	(48,40,42,50,210)	56	29	31	0.8	1	0.9
52	(11.75,9.938,6.625,4.49)	(47,39.75,39.75,50,431.04)	27	24	12	0.8	0.9	1

Dataset	1-Type of Horizontal Layer					2-Type of Horizontal Layer					3-Type of Horizontal Layer				
	Y_a	Y_b	Y_h	NB	PVU%	Y_a	Y_b	Y_h	NB	PVU%	Y_a	Y_b	Y_h	NB	PVU%
1	0	0	5	170	97.65	0	0	5	170	97.65	0	0	5	170	97.65
2	0	0	4	104	96.99	0	0	4	104	96.99	0	0	4	104	96.99
3	0	0	8	312	97.95	0	0	8	312	97.95	0	0	8	312	97.95
4	0	0	6	276	93.17	0	0	6	276	93.17	0	0	6	276	93.17
5	0	0	13	169	92.77	0	0	13	169	92.77	0	0	13	169	92.77
6	0	0	2	56	99.90	0	0	2	56	99.90	0	0	2	56	99.90
7	0	0	12	144	81.57	0	0	12	144	81.57	0	0	12	144	81.57
8	0	0	13	169	92.77	0	0	13	169	92.77	0	0	13	169	92.77
9	0	0	8	200	82.38	0	0	8	200	82.38	0	0	8	200	82.38
10	0	0	6	138	95.91	0	0	6	138	95.91	0	0	6	138	95.91
11	0	0	8	312	97.95	0	0	8	312	97.95	0	0	8	312	97.95
12	0	0	6	186	98.24	0	0	6	186	98.24	0	0	6	186	98.24
13	0	0	6	270	98.02	0	0	6	270	98.02	0	0	6	270	98.02
14	0	0	4	24	69.07	0	2	1	28	80.59	0	2	1	28	80.59
15	2	0	0	32	68.95	2	1	0	40	86.19	2	1	0	40	86.19
16	0	3	0	33	80.64	0	1	3	35	85.53	0	1	3	35	85.53
17	0	8	0	160	79.75	0	5	2	170	84.73	0	5	2	170	84.73
18	0	0	6	114	84.40	0	5	1	119	88.10	0	5	1	119	88.10
19	0	5	0	95	88.05	1	0	5	96	88.98	1	0	5	96	88.98
20	0	0	3	18	59.23	0	2	1	24	78.97	0	2	1	24	78.97
21	0	3	0	33	80.64	0	1	3	35	85.53	0	1	3	35	85.53
22	0	0	6	180	84.22	1	0	5	186	87.03	1	0	5	186	87.03

Dataset	1-Type of Horizontal Layer					2-Type of Horizontal Layer					3-Type of Horizontal Layer				
	Y_a	Y_b	Y_h	*NB*	*PVU%*	Y_a	Y_b	Y_h	*NB*	*PVU%*	Y_a	Y_b	Y_h	*NB*	*PVU%*
23	0	0	5	155	86.44	0	0	5	155	86.44	3	2	0	155	86.44
24	0	0	10	400	79.07	0	0	10	400	79.07	0	0	10	400	79.07
25	0	0	4	72	85.03	0	3	2	72	85.03	0	0	4	72	85.03
26	0	0	4	56	83.49	0	0	4	56	83.49	2	2	0	56	83.49
27	0	5	0	80	82.76	1	4	0	84	86.89	1	4	0	84	86.89
28	0	5	0	55	81.44	2	0	1	58	85.88	2	0	1	58	85.88
29	0	5	0	50	86.18	0	4	1	52	89.63	0	4	1	52	89.63
30	0	5	0	80	82.05	1	4	0	84	86.15	1	4	0	84	86.15
31	0	0	5	60	86.45	0	0	5	60	86.45	0	0	5	60	86.45
32	0	5	0	540	59.32	0	3	1	550	60.42	0	3	1	550	60.42
33	0	0	7	133	81.37	1	0	5	137	83.82	1	0	5	137	83.82
34	0	0	6	216	85.23	0	2	5	240	94.70	0	2	5	240	94.70
35	0	0	7	196	84.85	0	0	7	196	84.85	0	0	7	196	84.85
36	0	8	0	160	79.75	0	5	2	170	84.73	0	5	2	170	84.73
37	0	0	7	84	86.17	2	2	0	86	88.22	2	2	0	86	88.22
38	0	0	3	72	84.03	0	2	2	74	86.37	0	2	2	74	86.37
39	1	0	0	7	47.03	1	0	1	10	67.18	1	0	1	10	67.18
40	3	0	0	114	86.73	0	3	3	123	93.58	0	3	3	123	93.58
41	0	0	4	104	92.77	1	4	0	108	96.34	1	4	0	108	96.34
42	0	0	7	84	86.17	2	2	0	86	88.22	2	2	0	86	88.22
43	0	0	8	240	85.65	0	2	6	258	92.07	0	2	6	258	92.07
44	4	0	0	576	92.31	1	0	2	624	100.00	1	0	2	624	100.00
45	9	0	0	1296	93.10	8	0	1	1392	100.00	8	0	1	1392	100.00
46	4	0	0	408	91.54	2	0	1	444	99.62	2	0	1	444	99.62
47	0	0	8	200	87.04	0	4	1	209	90.96	2	2	1	217	94.44
48	0	0	4	64	82.60	0	0	4	64	82.60	0	0	4	64	82.60
49	0	0	5	100	87.85	0	0	5	100	87.85	0	0	5	100	87.85
50	0	0	5	135	85.78	0	0	5	135	85.78	0	0	5	135	85.78
51	0	7	0	203	84.63	0	4	3	209	87.14	0	4	3	209	87.14
52	3	0	0	81	84.38	0	3	1	84	87.50	1	2	1	87	90.63

Table 4. Total Number of Boxes per Pallet Considering the Mixed Horizontal Layers

3.3. The Maximum Number of Boxes per Pallet

The results reported in Table 4 present the maximum number of boxes loaded onto a pallet based on the results of the mathematical model. The relative humidity is 70%, the storage time equals 30 days, the pallet surface is gapped, the caliper is 0.16, *ECT* is 26, and *NoFR* is is/are 1, 2, and 3, respectively.

In the 1-dataset, 14-dataset, and 47-dataset, the maximum number of boxes is obtained when 1, 2, and 3 types of the horizontal layer are utilized to load boxes, respectively. The results show that using the mixed types of horizontal layers per pallet increases as the gap among the box dimensions increases. Therefore, the possibility to mix among the horizontal layers per pallet increases, which positively affects the *PVU%*. For example, the *PVU%* in the 52-dataset is 84.38, 87.50, and 90.63, when the number of horizontal layer types used is 1, 2, and 3, respectively.

As a result, the efficiency in using the different types of horizontal layers per pallet increases as the heterogeneity among the box dimensions increases, and *vice versa*.

Table 5 illustrates the ANOVA results for the impact of the number of horizontal layers on the *PVU%*. The tabulated results explain that there is a significant difference in the *PVU%*. Thus, the number of horizontal layers utilized to load the identical boxes into the pallet has an impact on the *PVU%*.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	476.08	2	238.04	3.23	0.042	3.055
Within Groups	11284	153	73.75			
Total	11760.07	155				

Table 5. The results of ANOVA for the impact of the number of layers used in the PVU%

3.4. Annual Average Morning Relative Humidity vs. Pallet Stability

The pallet stability is studied in terms of the load height and pallet stacked considering the annual average morning relative humidity in several cities in the USA (Table 6). Morning relative humidity values are recorded between 4 AM and 6 AM local standard time when usually relative humidity is the highest. The F_H decreases as the relative humidity increases which will affect the dynamic compression strength of the boxes. Therefore, the possibility of breaking boxes at the bottom increases as the relative humidity increases.

City	Annual Average Morning Relative humidity	F_H
Las Vegas, NV	40%	1.10
New York, NY	71%	0.80
Los Angeles, CA	79%	0.70
Columbus, OH	80%	0.70
Miami, FL	84%	0.70
Houston, TX	90%	0.50

Table 6. System Performance Related to the Annual Average Morning Relative Humidity at Several Cities

Box alignment, direction, pallet deck-board gap, and box shape influence the load height (pallet strength). The relative humidity has also the same role in reducing the dynamic compression strength of the boxes, which affects the pallet stability. For the same dataset, the box face with the highest dimension perpendicular to the base has the minimum dynamic compression strength. In this case, the number of boxes per pallet will increase; therefore, the average weight of the boxes will decrease.

Table 7 shows the load height for 52 datasets studied in this paper considering different values of the annual average morning relative humidity, where the storage time is 10 days. In the 1-dataset, the load height is 4.45, 4.13, 4.03, and 3.81, when the relative humidity is 40%, 71%, 79%-84%, and 90%, respectively. The results also show that an increase in relative humidity reduces the maximum number of boxes per pallet. For instance, in the 15-dataset and 41-dataset, the maximum number of boxes reduces from 40 to 26 and from 108 to 82, respectively, when the relative humidity increases from 40% to 90%. Considering this, the load height decreases as the annual average morning relative humidity increases. In Dataset 1, if the pallet is transferred from New York City to Houston City, the load height would be 3.81 to avoid any damages that might take a place.

Dataset	Load Height				Dataset	Load Height			
	RH					RH			
	40%	71%	79%, 80%, 84%	90%		40%	71%	79%, 80%, 84%	90%
1	4.45	4.13	4.03	3.81	27	1.65	1.52	1.48	1.56
2	4.64	4.33	4.23	4.03	28	1.20	1.11	1.08	1.02
3	9.13	8.48	8.26	7.82	29	1.44	1.33	1.29	1.76
4	13.84	12.85	12.52	11.86	30	1.78	1.64	1.60	1.68
5	1.59	1.47	1.42	6.29	31	3.45	3.19	3.10	2.92
6	12.39	11.58	11.31	10.76	32	8.95	8.26	8.03	7.57
7	1.68	1.55	1.50	1.44	33	8.34	7.74	7.55	7.15
8	1.56	1.44	1.40	6.16	34	4.28	3.95	3.84	3.62
9	11.91	10.99	10.68	10.07	35	4.13	3.81	3.71	3.49
10	3.03	2.80	2.72	2.56	36	2.45	2.26	2.20	2.07
11	9.83	9.13	8.89	8.42	37	7.13	6.61	6.44	6.10
12	2.91	2.70	2.63	2.50	38	3.66	3.38	3.28	3.10
13	12.85	11.93	11.63	11.01	39	1.26	1.17	1.14	0.77
14	1.26	1.16	1.13	2.79	40	2.19	2.02	1.97	1.86
15	1.14	1.05	1.02	1.99	41	1.44	1.33	1.29	2.18
16	1.33	1.23	1.23	2.48	42	7.13	6.61	6.44	6.10
17	2.45	2.26	2.20	2.07	43	2.52	2.33	2.26	2.13
18	5.25	4.85	4.71	4.44	44	10.48	9.67	17.13	8.86
19	5.16	4.76	4.63	4.36	45	4.44	4.10	6.89	3.75
20	1.47	1.35	1.32	2.77	46	11.54	10.64	29.34	9.75
21	1.32	1.22	1.22	2.45	47	8.64	7.98	7.75	7.31
22	2.52	2.34	2.28	2.16	48	2.88	2.67	2.60	2.47
23	2.61	2.41	2.34	2.21	49	10.71	9.94	9.68	9.17
24	21.6	19.93	19.37	18.26	50	9.47	8.79	8.57	8.11
25	2.07	1.92	1.87	1.21	51	15.36	14.17	13.78	12.98
26	1.63	1.57	1.30	1.61	52	4.15	3.82	3.72	3.50

Table 7. The Effect of Relative Humidity (RH) in the Load Height per Stacking Pallets

3.5. Storage Time vs. Pallet Stability

For reasons such as over-production, dynamic change in demand, and the seasonality of demand, the pallets must stay in the warehouses, distribution centers, or storage areas for some time (Li, Hua, Huang, Sheu, Cheng & Huang, 2020). The increase in storage time is one of the factors that diminishes the dynamic compression strength of boxes in the pallet loading problem (Table 2). The different storage times, 10 days (F_T = 0.65), 3 months (F_T = 0.55), and 4 months (F_T = 0.50), are studied in this section to explain the impact of the storage time on the pallet stability (load height), where it assumes that the relative humidity is 50% (F_H is 1), pallet surface is gapped, the caliper is 0.16, and *ECT* is 26.

The acquired results of the mathematical model in Table 8 show that the load height decreases as the storage time increases. For example, the load height in the 1-dataset is 4.43, 4.34, and 4.17, when the storage time is 10 days, 3 months, and 4 months, respectively. Thus, we could safely conclude that the increase in storage time results in a decrease in the load height within a constant relative humidity.

Dataset	Load Height			Dataset	Load Height		
	Storage Time				Storage Time		
	10 Days	3 Months	4 Months		10 Days	3 Months	4 Months
1	4.43	4.34	4.17	27	1.64	1.61	1.54
2	4.62	4.53	4.36	28	1.20	1.17	1.12
3	9.10	8.92	8.55	29	1.43	1.40	1.34
4	13.79	13.51	12.96	30	1.77	1.73	1.66
5	1.58	1.55	1.48	31	3.44	3.36	3.22
6	12.34	12.12	11.67	32	21.1	20.65	19.74
7	1.67	1.63	1.56	33	8.31	8.14	7.81
8	1.55	1.52	1.45	34	4.27	4.17	3.99
9	11.86	11.6	11.09	35	4.12	4.03	3.85
10	3.02	2.95	2.82	36	2.44	2.39	2.28
11	9.79	9.60	9.21	37	7.10	6.96	6.67
12	2.90	2.84	2.73	38	3.65	3.57	3.41
13	12.8	12.55	12.03	39	1.25	1.23	1.18
14	1.25	1.23	1.17	40	2.19	2.14	2.04
15	1.13	1.11	1.06	41	1.44	1.41	1.34
16	1.33	1.30	1.24	42	7.10	6.96	6.67
17	2.44	2.39	2.28	43	2.51	2.46	2.35
18	5.23	5.12	4.89	44	10.44	10.21	9.76
19	5.14	5.03	4.80	45	4.42	4.33	4.14
20	1.46	1.43	1.37	46	11.49	11.24	10.74
21	1.31	1.28	1.23	47	8.61	8.42	8.05
22	2.51	2.46	2.36	48	2.87	2.81	2.69
23	2.60	2.54	2.43	49	10.66	10.45	10.02
24	21.51	21.04	20.12	50	9.43	9.24	8.87
25	2.06	2.02	1.94	51	15.29	14.96	14.30
26	1.63	1.59	1.35	52	4.13	4.04	3.86

Table 8. The Effect of Storage Time on the Load Height

3.6. The Effect of the Annual Average Morning Relative Humidity vs. Storage Time on the Load Height

The comparisons in terms of either the effect of relative humidity change or the effect of storage time change on the load height are made based on a %Reduction in the load height for each dataset as follows:

$$\%\text{ Reduction in the Load Height} = \frac{LH_{max} - LH_{min}}{LH_{max}} \times 100 \tag{19}$$

Where LH_{max} is the maximum load height; LH_{min} is the minimum load height.

Based on the results depicted in Figure 7, it is easy to observe that the relative humidity has a significant impact on the pallet stability (load height) compared with the storage time. The reduction in the load height based on the change in the relative humidity is less than 25% in 38 out of 52 datasets. The maximum %reduction in the load height is greater than 77.00; it occurs in 5- and 8-datasets, where the identical box dimensions are strongly heterogeneous. Meanwhile, the minimum %reduction in the load height is less than 10.00; it obtains by 27- and 30-datasets, where the dimensions of the identical boxes are weakly heterogeneous. On the other hand, the reduction in the load height based on the change in storage time in the datasets is less than 10% except for the 26-dataset, where the reduction in the load height is around 18%. The identical box dimensions in this dataset (26-dataset) are slightly heterogeneous. The box dimensions also have an impact on the load height as the storage time increases. Therefore, the max load height changes dynamically along with box dimension, max stack height of the pallet, the pattern of the pallet load, and many other factors.

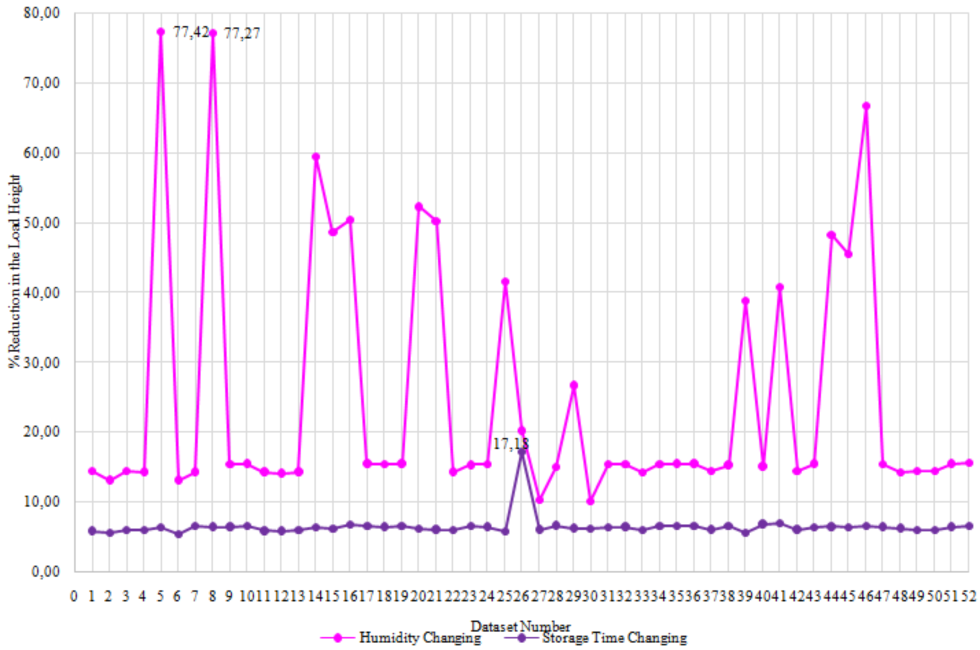


Figure 7. %Reduction in the Load Height

4. Conclusion

In this paper, two-phase heuristic algorithm was proposed to tackle the 3-dimensional pallet loading problem with identical boxes considering two performance measures pallet volume utilization and stability, where the overlapping and overhanging among boxes were not allowed. Additionally, the impacts of the interlock stacking pattern, relative humidity, and storage time were studied. The findings showed that the ability of the propounded algorithm in maximizing the pallet volume utilization increased as the number of horizontal layers per pallet increased, as well as the heterogeneity amongst the box dimensions increased, where the identical boxes were assigned to be loaded into a pallet. Typically, the use of two or three types of horizontal layers simultaneously leads to creating the interlocking stacking pattern, which reduces the dynamic compression strength of the box by up to 60%, while it improves the stability of the pallet because of the friction force among the horizontal layers. The storage environment also influences pallet strength, where the high humidity and long storage time under load both reduce strength by up to 50%. Other factors that can reduce pallet strength include but are not limited to the overhang of boxes, pallet deck-board gap, box shape, and material.

Further, the minimum total number of boxes per horizontal layer was obtained when the shortest dimension was perpendicular to the base, while the maximum number of boxes was achieved when the longest dimension of the box was perpendicular to the base. Meanwhile, the maximum and the minimum dynamic compression strength were acquired when the shortest and longest dimensions of the box were perpendicular to the base, respectively. This leads to conclude that the minimum average weight on the boxes at the bottom was obtained when the number of boxes per horizontal layer was higher (minimum dynamic compression strength), and *vice versa*.

Moreover, the dynamic compression strength of the box decreased as the relative humidity and storage time increased. Considering the %reduction in the load height, the relative humidity had more impact on the box's mechanical strength compared to the storage time. The relative humidity and storage time could reduce the load height up to 25% and 10% in most of the datasets, respectively. On the other hand, it is recommended to load a pallet considering the place with high relative humidity in case it is moved among different places with different relative humidity. Finally, the box's material, direction, box dimensions, characteristics of pallet, and interlocking stacking pattern had a dramatic impact on the two performance measures, pallet volume utilization, and stability.

For future work, it is recommended to consider maximizing utilization while considering overlap and overhang for homogenous and heterogenous box sizes, using meta-heuristics to solve real-life problems for both groups of the pallet loading problem, uniform pallet loading problem and, and distributors pallet loading problem, as well as the machine learning algorithms.

Declaration of Conflicting Interests

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