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Optimizing warehouse operations for environmental sustainability: A simulation study for reducing carbon emissions and maximizing space utilization

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C H R O N I C L E

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A B S T R A C T

Loading and unloading operations for Stock Keeping Units (SKUs) in warehouses are critical to logistics management systems. However, these operations also have a significant impact on the environment, particularly in terms of carbon dioxide (CO2) emissions. As such, warehouse management must consider not only operational efficiency but also environmental impact. The reduction of CO2 emissions in warehouses is becoming increasingly important, both for legal compliance and to meet sustainability targets. In this article, we will emphasize the environmental impact of warehouse operations, particularly on CO2 emissions, and explore ways to minimize them while still maximizing warehouse performance. We will review various optimization models proposed to address this issue and highlight the importance of considering environmental objectives when designing warehouse operations. We will also describe a simulation study conducted to determine the Pareto optimal frontier for a warehouse design, considering transportation, space utilization, and CO2 emissions. The outcomes of implementing this simulation's results include reduced CO2 emissions and increased space utilization, which demonstrate the potential benefits of considering environmental objectives in warehouse design and management.

1. Introduction

Warehousing plays a significant role in the world's economy, as many organizations' assets are stored in warehouse inventories. However, managing warehouses can be complex and costly from 2% up to 5% of sale costs for a company rooted in warehousing (Larson et al., 1997), so organizations strive to implement the most efficient procedures to minimize costs. The history of warehousing has been marked by the diversity and complexity of organizations and the various problems and issues that have arisen. To address these issues and improve the efficiency of warehouse operations, organizations need to adopt a coherent, coordinated, and acceptable system that enables proper communication and coordination among all its components. This system should be based on predetermined goals and a clear strategy, enabling all parts of the organization to work together effectively. By following such a system, organizations can optimize their warehouse operations and improve the overall efficiency of their operations. Value added warehousing and distribution (VAWD) refers to the activities that enhance warehousing and freight transportation by managing the flow of products through a distribution facility. VAWD can reduce storing, enhance product flow, and enable customization (Statista, 2020). The growing sector of VAWD in the logistics industry as more companies look to streamline their supply chain operations and reduce costs. In 2018, the segment saw gross revenue growth of 8% to $43.3 billion, the best result since 2011. Net revenue grew 6.3% to $33.1 billion (Statista, 2020).

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A warehouse plays a vital role in the operations of any organization. It is a place where goods are stored, sorted, and prepared for distribution or transport. Warehouses are a crucial link in the supply chain, ensuring that products are available when and where they are needed. However, the tasks and responsibilities of warehouses have become more complex in recent years as organizations have increasingly diverse and specific requirements. Modern warehouses can fulfil other purposes such as same day shipments, managing returned products, late configuration, quick response to customer needs, labelling and tagging (Zhang & Khan, 2017). Optimizing space utilization in a warehouse involves maximizing the amount of storage space available while minimizing the amount of unnecessary or wasted space. This problem attracted authors' attention and many works addressed it (Benson, 2008; Larson et al., 1997; Liu et al., 2006; Mohsen & Hassan, 2002; Shetty et al., 2016; Suvittawat, 2016; Zhang et al., 2021).

Optimum space utilization can be achieved through various methods, such as carefully planning the layout and design of the warehouse, implementing efficient storage systems, and using advanced technology to track and manage inventory. One way to optimize space utilization is to carefully plan the layout of the warehouse. This might involve determining the optimal location for different types of goods, considering factors such as their size, weight, and frequency of use. It might also involve designing the warehouse to make use of vertical space, such as using mezzanines or shelving systems (Y. Tan et al., 2019). Another approach to optimizing space utilization is to implement efficient storage systems, such as pallet racking (Baldassino & Bernuzzi, 2000) or bulk storage systems (Xu & Burfoot, 1999).

These systems allow for the efficient use of space by allowing goods to be stored in a compact and organized manner. Finally, using advanced technology, such as inventory management software (Atieh et al., 2016), can also help to optimize space utilization. This software can track the movement and storage of goods in real-time, allowing warehouse managers to identify any areas of wasted space and make changes to improve efficiency. Overall, optimizing space utilization is an important factor in the successful operation of any warehouse, as it can help to reduce costs and increase the efficiency of the storage and distribution process.

There are three major operating policies regarding storage space management: dedicated, shared, and class-based. For dedicated policy, a specific lane will be dedicated to an SKU (even if the lane is empty, no other SKU will be stored there). In shared policy, other SKUs can use the space if a lane becomes empty. For the case of class-based, only SKUs with similar characteristics (such as size) can be stored in a specific lane. The shared policy provides the highest efficiency of space utilization, and the class-based policy will be next in the ranking. Another important concept related to this problem is honeycombing. Honeycombing happens when a lane has some empty spaces that cannot be used for other SKUs as the lane is not completely empty. In general, shallow lanes cause more honeycombing and less aisles. In contrast, deeper lines will lead to less honeycombing and more aisles (Derhami et al., 2020).

Creating sustainable environments in different settings such as sustainable cities (Rajabi et al., 2023), sustainable drones (Beigi et al., 2022) has attracted authors' attention recently. Creating a sustainable warehouse is related to managing, integrating, and balancing environmental and economic aspects of warehouse operations (K.-S. Tan et al., 2009). Reducing gas emissions of lift trucks is crucial to improve warehouse operations' sustainability (Boenzi et al., 2015; Carli et al., 2020; Pashkevich et al., 2019). The layout of a warehouse can affect the total distance that a lift truck covers and, therefore, the total amount of gas emission.

2. Literature Review

Policy analysis is a systematic and evidence-based approach to understanding public policies and their effects. It involves the use of various methods and techniques to evaluate the design, implementation, and outcomes of policies. The goal of policy analysis is to provide decision-makers with relevant information and insights that can help them make informed decisions about policy choices. Policy analysis is a versatile tool that can be applied in a variety of fields, including healthcare (Sahebi-Fakhrabad et al., 2023), natural resource management (Yoosefdoost et al., 2022), sustainable supply chain (Sadeghi, Bani, et al., 2023), social welfare, and more, to provide valuable insights into policy design and implementation. Policy analysis is a crucial aspect of effective warehouse management, particularly when it comes to selecting the optimal lane depth. This decision directly affects the efficiency of a warehouse, as well as the amount of wasted space. To address this issue, numerous researchers have conducted investigations into designing and modelling different components of the problem. By carefully analysing the available data and considering various factors, policymakers can make informed decisions that improve warehouse performance and reduce costs.

As one of the earliest models related to this problem, Goetschalckx and Donald Ratldff (1991) developed a layout procedure that can determine the best lane depth from a list of possible depths. Their method also specifies the number of aisles and lanes for the multiple-product scenario. They compared the quality of their proposed procedure and some other heuristics with the results of an optimal approach with no limitation on the possible depths. They claimed their method would require the minimum warehouse space if the warehouse were balanced perfectly. They also demonstrated that the ideal lane depth follows a triangular pattern. Larson et al. (1997) proposed a heuristic approach for designing a warehouse layout in which a dual objective function maximized space utilization and minimized transportation costs. The researchers aimed to classify warehouses based on storing SKUs and input supply relative to the required storage space. This method sorts of classes based on their average ratios and structures and allocates storage spaces to classes according to their required rankings and space. Also, the honeycomb effect, fluctuations in inventory level, and maximum accumulation height are considered to determine an SKU's storage space, and the stochastic storage policy is predicted between classes.

Petersen and Aase (2004) compared the picking, storage, and routing policies in manual order picking. They investigated the effect of three process decisions, picking, storage, and routing, on order picker travel, which is a significant cost component of order fulfilment. Additionally, they examined the effect of order size, warehouse shape, pick-up/drop-off point location, and demand distribution on performance. They also evaluated several picking and storage operations, which provided the most significant percent savings relative to the current baseline policies and examined their effect relative to other factors.

Derhami et al. (2017) performed a study on determining warehouses' optimal storage lane depth to maximize efficiency. They evaluated the optimal depth of an aisle between the lanes under the wasted space index. This article states that block stacking is an inexpensive storage system widely used in manufacturing systems. In this approach, the Stock Keeping Units (SKUs) pallets are stacked in a warehouse with a limited production rate. However, determining the optimal lane depth maximizes space utilization under limited production rate constraints has yet to receive sufficient attention in the literature and is an open issue. This paper proposes mathematical models to achieve the optimal lane depth for single and multiple SKUs where pallet production rates are limited (in contrast to Goetschalckx and Donald Ratldff (1991), that considered single SKU and infinite production rate). A simulation is also carried out based on stochastic uncertainty in the main parameters of production and demand to evaluate the proposed models' performance. They later introduced another model to consider a space-efficient layout for block-stacking warehouses (Derhami et al., 2019). It was shown that the common lane depth (CLD) model would not be suitable for locating bay depths for a layout and an appropriate waste function was introduced to find the whole waste of storage volume in the layout. The simulation experiments showed that the layouts produced by non-CLD models always generate less waste of storage volume than those obtained by the CLD model.

Venkitasubramony and Adil (2019) considered stochastic and dynamic production flow as considering a deterministic and uniform inflow will end in underestimation of the needed space. They introduced a scenario-based model that can help in decisions related to lane depth, warehouse size, leasing extra space, etc. The authors proposed a sequential decision model that has a form of a tree with future operating scenarios as branches. In terms of infeasibility avoidance and risk reduction, their method provides robust solutions. Maniezzo et al. (2021) studied the pre-marshalling of the block stacking warehouse in a stochastic setting. pre-marshalling is the process of reordering SKUs in the lane to make future retrievals easier. In their problem, the retrieval orders are not known beforehand. They utilized heuristic data to generate a statistical model that forecasts future orders. Then they used the forecasts as inputs for a two-stage stochastic optimization model. In the first stage, they solve a pre-marshalling problem, and then they solve a block relocation problem. They used eight real-world instances and some randomly created data to showcase the efficiency of their proposed approach. Table 1 summarized the literature review related to block stacking storage systems.

Table 1
An overview of block stacking storage systems literature

Reference	Objective function	Production Rate		SKU		Problem		Solution Method
		Finite	Infinite	Single	Multiple	Deterministic	Stochastic	
(Goetschalckx & Donald Ratldff, 1991)	Space utilization		√	√		√		Dynamic programming
(Larson et al., 1997)	Space utilization	√			√		√	Heuristic optimization
(Petersen & Aase, 2004)	Fulfillment time		√		√		√	Simulation
(Derhami et al., 2017)	Space utilization	√	√	√	√		√	Mathematical model
(Derhami et al., 2019)	Space utilization	√			√		√	Non-linear mathematical model
(Maniezzo et al., 2021)	Reshuffling cost		√		√		√	Two-stage stochastic optimization dynamic programming
(Pfrommer et al., 2022)	Space utilization	√			√	√		Simulation
(Sadeghi, Sun, et al., 2023)	Transportation costs		√	√		√		Robust optimization
(Sadeghi, Bani, et al., 2023)	Fulfillment cost	√			√		√	Chance constraint optimization

Another critical factor we considered in our work is exhaust emissions in lift trucks. As Groves and Cain showed in their survey, the highest amount of exposure to diesel engine exhaust emission occurs in environments where forklift trucks are typical (Groves & Cain, 2000). However, lift trucks are a cheaper and (in case of fire) safer option for indoor use (Mikkonen et al., 1995). Mikkonen et al. (1995) addressed the problem of Forklift Truck emissions. They quantified the effect of using a reformulated diesel fuel instead of a regular one. As a result of using the new diesel, the Sulfur amount in the air was reduced from 605 ppm to 7 ppm. Javadi et al. (2021) estimated the total amount of gas emission for the second major automaker manufacturer in Iran. In their work, they distinguished between heavy-duty and light-duty lift trucks. Pashangpour et al. (2018) suggested using an electric lift truck to reduce gas emissions. They introduced a scheduling problem for a sugarcane factory and optimized the amount of emissions. They demonstrated the effectiveness of using biomass electric power generation (and using the electricity for lift truck charging) to reduce gas emissions and general costs. Another study pointed out a gap in the literature for the interaction between warehouse and inventory management and those impacts on the environment (Fichtinger et al., 2015). They created a simulation model, and their results showed the effect of inventory management on greenhouse gas emissions in warehouses is significant. As one of the first tries, Atashi Khoei et al., 2023 considered the problem of energy minimizing order picker forklift routing problem (EMFRP). They introduced a mixed integer programming modelling approach and dynamic programming to solve the small instances of the problem. They combined two heuristics, tour construction, and tour improvement, into a single solution method for the larger problems. We presented the literature related to gas emission of trucks in Table 2.

Table 2
An overview of literature related to gas emissions of lift trucks

Reference	Methodology	Results
(Mikkonen et al., 1995)	Quantified amount of emissions for forklifts that work in warehouse when they used a regular or reformulated diesel fuel for lift trucks	As a result of using the new diesel, the Sulfur amount in the air was reduced from 605 ppm to 7 ppm.
(Groves & Cain, 2000)	Visited forty sites and evaluated exposure to diesel engine exhaust emissions	The highest amount of exposure to diesel engine exhaust emission occurs in environments where forklift trucks are typical
(Fichtinger et al., 2015)	Designed an integrated simulation model to assess the interaction between inventory management and greenhouse gas emissions	They showed the effect of inventory management on greenhouse gas emissions in warehouses is significant.
(Pashangpour et al., 2018)	They solved a scheduling problem for a large-scale sugarcane factory that has solar resources, electric lift trucks, and a thermal unit. They optimized costs and gas emissions.	They demonstrated the effectiveness of using biomass electric power generation (and using the electricity for lift truck charging) can reduce gas emissions and general costs
(Javadi et al., 2021)	Utilized a Radial Basis Function (RBF) network model to predict Co2e emissions in an automotive manufacturing company.	Their model captured 88 percent of the variation of CO2 emissions (including emissions from lift trucks)
(Atashi Khoei et al., 2023)	Developed a mixed integer programming model and a dynamic programming for small cases. For larger cases, introduced a heuristic that combines tour construction and tour improvement.	The results confirmed the quality of the solutions that the heuristics provide for the larger cases.

Conventional approaches to the layout design of block stacked warehouses assume perfect staggering of product inflow leading to perfect sharing of space among products. Since such an assumption is seldom valid, this paper takes a fresh look at the block-stacked layout problem, modelling the effect of imperfectly staggered product arrivals using queuing theory. In this paper, analytical expressions are derived for arrival time and processing time coefficients of variation using warehouse parameters and design variables (Venkitasubramony & Adil, 2021).

3. Problem Statement

To determine the optimal lane depth for storing a multi-product, it is necessary to consider three important factors. Firstly, it is important to determine the amount of space required for each lane. Secondly, it is necessary to consider how long the product will be occupying this space. In addition, it is important to consider the sustainability factor of CO2 emissions when determining the optimal lane depth for storing a multi-product. By considering sustainability factors, we can make informed decisions that not only optimize storage space and cost but also minimize environmental impact. The main three objectives in this problem are 1) space utilization, 2) forklift transportation inside the warehouse, and 3) environmental impact. The first goal is equivalent to wasted storage space in the warehouse and it should be noted that minimizing the wasted storage space is equivalent to maximizing space utilization. Hence, if a model that maximizes space utilization is achieved, it can be claimed that the optimal depth in storage is achieved. For the second goal, it is important to factor in the cost of accessing each SKU block during storage, such as forklift transportation. The third objective can be achieved by analyzing the emissions associated with accessing each SKU block during storage, as well as the emissions associated with the transportation of the products to and from the storage facility.

3.1. Objective Functions

In this section, we will provide a detailed explanation of how to calculate the three primary objectives of this problem, which include maximizing space utilization, optimizing forklift transportation within the warehouse, and reducing environmental impact.

3.1.1. Space Utilization

The types of wasted space in the model include the following two modes:

I. Wasted storage space: "honeycomb effect"

In the context of inventory management, the honeycombing effect refers to the inefficient use of storage space in a warehouse or distribution center. This occurs when large items or bulky products are stored in small storage locations, leaving empty spaces around them that cannot be utilized for other items (Derhami et al., 2017). The term "honeycombing" is used because the storage layout can resemble a honeycomb pattern, with irregular empty spaces in between items. This results in wasted storage capacity, which can lead to higher inventory holding costs and less efficient use of warehouse space (Derhami et al., 2019). The honeycombing effect requires assigning the entire lane to a particular SKU after placing the first pallet from the storage lane, as shown in Fig. 1.

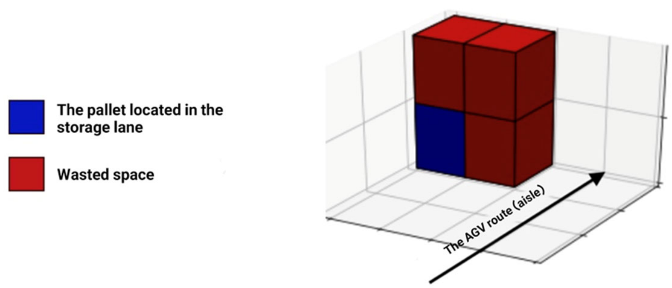

Fig. 1. The wasted storage space due to the "honeycomb effect"

II. Wasted storage space: Aisle

Although aisles themselves are not utilized for storing goods, they are essential for providing access to the stored SKU pallets. Therefore, designers need to consider various strategies to minimize both the honeycomb effect and aisle-related waste. One common approach is to optimize the warehouse layout and reduce aisle widths to their minimum functional requirements. Narrower aisles may limit the size of forklifts or other material-handling equipment that can be used, but they can also create more available storage space. To model the storage and retrieval system in a warehouse accurately, designers often consider a fixed width requirement for forklifts to move safely and efficiently without any hazards. This width is usually relative to the size of the SKU pallets being stored and retrieved. The width must be large enough to accommodate the forklift and its load but not so large that it wastes space or compromises safety. Figure 2 illustrates the scenario when the required aisle width is two SKU widths. The figure depicts how this aisle width requirement impacts the overall layout and design of the space, including the placement of pallets.

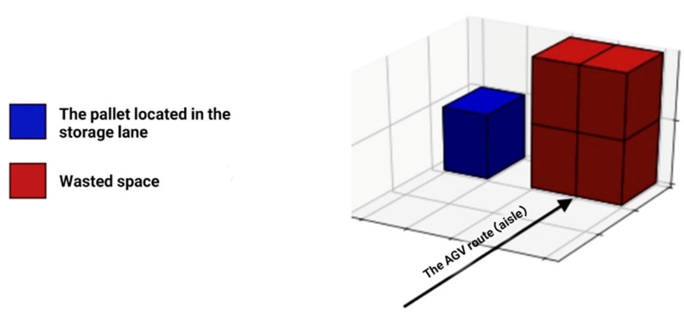

Fig. 2. The wasted storage space due to the aisles

3.1.2. Transportation Cost

The following rule is also used to calculate the distance travelled by AGVs (or forklifts) in the warehouse:

- The travel in K-direction: The travel in the aisle to reach the corresponding lane,
- The travel in X-direction: The travel in depth by the AGV to place the pallet,
- The travel in Z-direction: Lifting the pallet and storing it by the block-stacking method.

Fig. 3 shows the transportation calculation from the dock in addition to the placement of the first pallet.

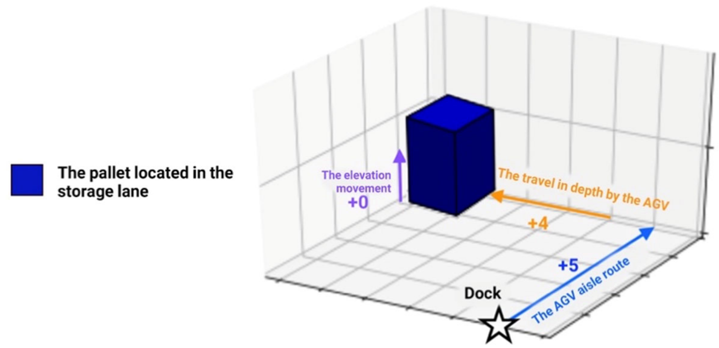

Fig. 3. The distance travelled by a pallet from the dock to the final location in the warehouse

3.1.3. Environmental Cost

For environmental effects we will calculate the CO2 emissions for two types of motors: diesel and LPG. Moreover, we will distinguish between the amount of emissions when a lift truck is loaded or unloaded. To calculate the amount of CO2 emissions, we used Ziółkowski et al. (2022) analyses. They tested lift trucks that used LPG and diesel as fuel and calculated the amount of emissions in different situations. Based on their investigations, fuel consumption for a lift truck with a diesel motor is 96 liter/100 KM when it is under load and 55 liter/100 KM when the lift truck does not carry any load. These numbers will be 168 liter/100 KM and 84 liter/100 KM for a lift truck with LPG fuel. We also know that the CO2 emission of a liter of diesel is 2.7 KG (Jakhrani et al., 2012). Therefore, we will have these formulas for CO2 emissions for forklifts with a diesel and an LPG motor, respectively:

$$\text{Disel Emissions} = (\text{ltd} \times 96 \times 2.7 \times 10^5) + (\text{utd} \times 55 \times 2.7 \times 10^5) \tag{1}$$

$$\text{LPG Emissions} = (\text{ltd} \times 168 \times 1.51 \times 10^5) + (\text{utd} \times 84 \times 1.51 \times 10^5) \tag{2}$$

where *ltd* shows the loaded travelled distance and *utd* stands for unloaded travelled distance in meters.

3.2. Simulation Model

In this study, the exchange between selecting the appropriate depth and width of storage in the warehouse is investigated. Also, by simulating the literature models, an attempt is made to minimize the warehouse's wasted space, transportation, and CO2 emission. The following assumptions are made in the present study:

- The primary storage of released goods is presumed.
- The proposed model is developed for a limited production rate.
- Due to the limited production rate, the proposed model and the simulation results are suitable for production systems where pallets are stored at a limited production rate.
- The studied model and its results are presented to maximize volume space instead of floor area.

Also, only the single objective optimization of maximizing the used space in warehouse logistics is mentioned in the literature. In this research, a proposed model for optimizing transportation within the warehouse is provided and applying existing models and simulating the problem as well as the environmental effects. In general, the number of SKUs stored in a warehouse is too high to assign all SKUs to the desired lane depth and arrange all lane depths in the warehouse. The optimal shared lane depth is calculated to address this issue - the shared storage depth that minimizes the total waste for multiple SKUs.

The models in this study are assumed to be the product categories that include Q pallets of n SKU types and are evacuated from the warehouse with the same classification. Production is at the rate of P pallets per unit time, and the stacked blocks are placed in lanes with the depth of X pallets and the height of Z pallets. Pallets decrease at a rate of λ pallets per unit time, and aisles with the width of a pallets are required to access the lanes. During the entry/exit of pallets to/from the warehouse, two types of wasted space occur due to aisles (W_A) and the honeycomb effect (W_H). Also, the value of the distance travelled by the pallet (TP), CO2 emission (EC) is measured per event. Eventually, the average transportation, wasted space, and emissions.

Algorithm 1: Simulation Modeling Framework

```
Initialize parameters (P_i, λ_i, Q_i, z, x, a, n)
Scheduling the entrance of the first event for all SKUs
while the simulating time is not over do
    Find the nearest event
    if the event is of type pallet entry then
        if lane in the warehouse and it is of the current SKU type then
            Assign the pallet to one of these lanes with this SKU
        end
        else
            Determine a new lane to replace the current SKU Assign the pallet to
             that line else
                // It is known that this is not an entry event (because
                   there are only two events of entry or exit for
                   pallets)
                if there is a half-full lane in the warehouse and it is of the current SKU
                 type then
                    Deplete the pallet from this lane
                end
                else
                    Deplete the pallets from one of the full lanes
                end
            end
        end
    end
    Update the status of lanes and coordinates (full or empty)
    Calculate the values of W_H, W_A, TP, EC
    Schedule the entry of the next event (pallet and SKU type)
end
return Average Space Waste (W̄), Transportation (T̄P), Emission (ĒC)
```

Fig. 4. Developed discrete event Simulation algorithm

After determining the statistical distribution of entry/exit rates of pallets to the warehouse based on entry times and following a Poisson process, the time between them is considered an exponential distribution with the average rate of entry/exit of SKUs. The Poisson process is a model for displaying a sequence of events with discrete values. The Poisson process's memory-less feature denotes that the occurrence of an event is independent of previous events.

4. Results

In this study, we investigated the average transportation, wasted space, and emissions associated with the evacuation of product categories, which include Q pallets of n SKU types from a warehouse. The models were analyzed with respect to the production rate of P pallets per unit time and the pallets' decay rate of λ pallets per unit time. In terms of the simulation parameters, we assumed a range for the production rate P to be between 100 to 500 pallets per hour, and the pallets' decay rate λ to be between 1 to 10 pallets per hour. The stacked blocks were placed in lanes with the depth of X pallets and the height of Z pallets. Aisles with the width of a pallet were required to access the lanes, leading to two types of wasted space, namely W_A and the honeycomb effect (W_H), during the entry/exit of pallets to/from the warehouse. To evaluate the transportation performance, we measured the distance traveled by the pallets (TP) and CO2 emission (EC) per event. Based on the results presented in Fig. 5, it can be concluded that the average transportation distance (TP) decreases as the depth of the lanes (x) increases. This can be seen by comparing the values of TP for x=1 and x=9, which are 12497.9 and 6149.6, respectively. Similarly, the amount of wasted space due to aisles (waste_A) and honeycomb effect (waste_H) also decrease as x increases, indicating that deeper lanes lead to more efficient use of space. It is also observed that the value of k has a significant effect on the amount of wasted space. As the number of SKU types (k) decreases from 17 to 3, the amount of wasted space due to aisles (waste_A) and honeycomb effect (waste_H) decreases. This is because as the number of SKU types decreases, the amount of rearrangement needed to fill the pallets decreases, leading to less wasted space. Furthermore, it is observed that the total CO2 emission (both diesel and LPG) increases with the depth of the lanes (x) and the amount of wasted space due to aisles (waste_A). This can be attributed to the fact that deeper lanes and more aisles lead to longer travel distances and higher fuel consumption, resulting in increased emissions.

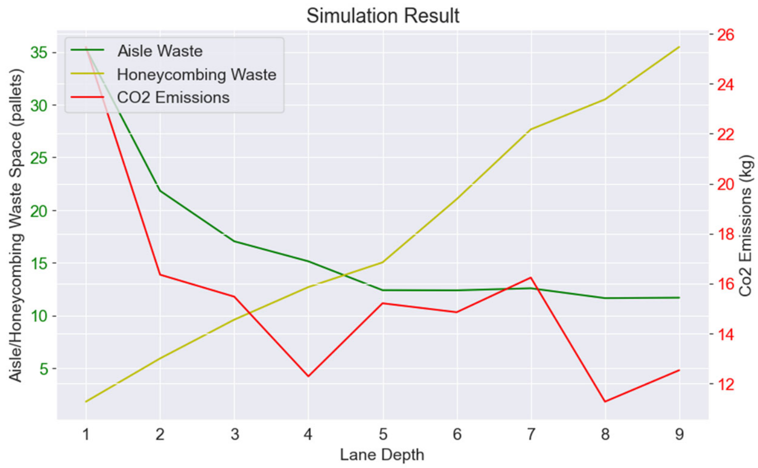

Fig. 5. Simulation results for different lane depth

Pareto frontier, also known as Pareto efficient front or Pareto set, is a powerful analytical tool used to identify optimal trade-offs between two or more conflicting objectives. The frontier represents the boundary of the best possible outcomes, where any improvement in one objective requires sacrificing some amount of another. The Pareto frontier is useful for decision-making in various fields, including economics, engineering, and environmental management. It can help identify the most efficient and effective solutions to problems by providing decision-makers with a set of options that achieve the best possible outcomes for each objective. By analyzing the Pareto frontier, researchers can determine which trade-offs are most acceptable and which solutions should be considered for implementation. The Pareto frontier results in Fig. 6 for aisle waste versus honeycombing waste show a clear trade-off between the two factors. As honeycombing waste decreases, aisle waste increases, and vice versa. This means that it's impossible to improve both factors simultaneously. The manager needs to decide which factor is more important for the company and choose the point on the frontier that corresponds to the best trade-off between the two factors. For example, if the company is more concerned about reducing honeycombing waste, they might choose the point with the lowest honeycombing waste even if it means accepting higher aisle waste. On the other hand, if the company is more concerned about reducing aisle waste, they might choose the point with the lowest aisle waste even if it means accepting higher honeycombing waste. The Pareto frontier provides a useful tool for visualizing the trade-off and making informed decisions. Similarliy the same pareto frontiers are provided for CO2 emssion and fork lift movements in Fig. 7 and Fig. 8.

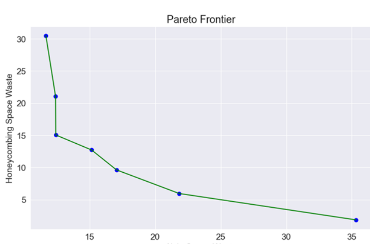

Fig. 6. Pareto frontier for honey-combing waste vs. aisle waste

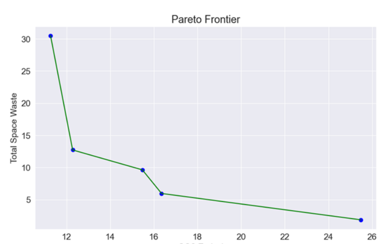

Fig. 7. Pareto frontier for space waste vs. CO2 emissions

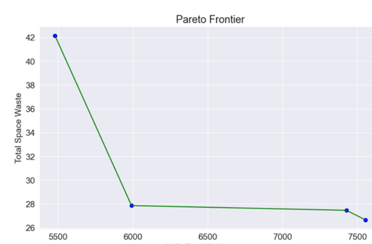

Fig. 8. Pareto frontier for space waste vs. transportation

The results indicated that the production rate and pallet decay rate significantly affect the transportation performance, wasted space, and emissions associated with the evacuation of product categories from a warehouse. These findings can be used to optimize the evacuation process and minimize the associated environmental impact.

5. Conclusion

Machine learning and mathematical modelling are two essential tools used in various fields, including business, engineering, healthcare, and science (Mousavi et al., 2023). These tools help experts and professionals to make sense of complex and large data sets, derive insights, and make informed decisions. With the ever-increasing complexity of business operations, companies are turning to machine learning algorithms to optimize processes and reduce costs (Taghiyeh et al., 2020). Mathematical modelling can also be used to optimize transportation and logistics, ensuring that goods are transported in the most efficient and environmentally friendly way possible. Optimization of block-stacking operations using mathematical modelling is crucial to achieve efficient warehouse management. This study proposed a three-objective model that considers the wasted space and transportation of goods in the warehouse, and environmental effect. The discrete feed-forward simulation approach was used to evaluate the model's performance, and the results were promising. The numerical example demonstrated that the proposed model can accurately determine the optimal storage depth, reduce the amount of wasted space and transportation and CO2 emissions. The findings of this study provide valuable insights for warehouse managers and operators. By optimizing the storage depth, they can significantly reduce the warehouse's operating costs while improving the overall efficiency of the warehouse. Furthermore, the proposed model can help in identifying the optimal block-stacking conditions, such as the honeycombing effect, which can further enhance the warehouse's space utilization. However, this study has several limitations that need to be addressed in future research. Firstly, the proposed model was evaluated under the assumption of unlimited warehouse capacity. Future studies should investigate the model's performance under warehouses with limited capacity. Secondly, the model did not consider the case of multiple sources of transporting pallets. Therefore, future research should investigate this case to determine the optimal storage depth and block-stacking conditions. Thirdly, the proposed model did not integrate location and routing problems. Therefore, future studies should consider these problems to optimize the overall warehouse management. Fourthly, the proposed model can benefit from the use of heuristic and hyper-heuristic algorithms to solve the groups of products and customers. Finally, the study suggests the need for reviewing and redesigning the network to achieve optimal warehouse management.

In conclusion, this study provides valuable insights for optimizing block-stacking operations in warehouses. By considering the wasted space and transportation of goods, the proposed model can accurately determine the optimal storage depth and block-stacking conditions. Future research should address the limitations of the proposed model and investigate the integration of location and routing problems, as well as the use of heuristic and hyper-heuristic algorithms to solve the groups of products and customers. By addressing these limitations, warehouse managers and operators can achieve optimal warehouse management, reduce operating costs, and improve overall efficiency.

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