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An Efficient Approach to Investigate the Tradeoff between Double Handling and Needed Capacity in Automated Distribution Centers

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Abstract: Sustainable techniques in distribution centers, such as automation that reduces the land area needed, can be utilized. Automated Storage and Retrieval Systems (AS/RS) are used to efficiently manage the flow of pallets and carton cases in distribution centers. There are two types of AS/RS: one for pallets and another type for cases that are depalletized from pallets. Further enhancements on the system are obtained by investigating both warehouses together. This paper investigates an efficient approach that directly affects the conceptual design of automated distribution centers for the purpose of reducing the total costs. The tradeoff between the throughput (defined by the level of double handling) and warehouse capacity is investigated in this study by finding the best lot sizing rules for different classes of products (A, B, and C). These rules are to determine the method of moving carton cases from the first warehouse to the second one. The number of stacker cranes is determined based on the found throughput. The effect of double handling of pallets on the design is considered for the first time in this study. Analytical formulas and simulation were used to find the throughput and capacity based on the mentioned lot sizing rules. Then, an integer nonlinear model was developed to optimize the system. According to the results of the assumed data, the model can save up to 19.5%. The costs of stacker cranes were found to account for approximately 78.7% of the total costs in the best solution found. A decision support system has been developed to help decision makers find an efficient design of distribution center.

Keywords: Automated Storage and Retrieval System; material flow; warehouses; throughput; conceptual design; double handling; ABC analysis

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1. Introduction

Among the drivers for sustainable supply chains is automation, which is essential for long-term sustainability goals [1]. Automation in distribution centers can also enhance the resilience of the supply chain. Using automation in warehouses is considered as a green solution since it reduces the land area needed in the warehouse, where the area is utilized horizontally and vertically by using high-bay warehouses [2]. Green warehouse designs that reduce CO_2 emissions were found in the literature [3]. Stacker cranes are one important type for automation where Automated Storage and Retrieval Systems (AS/RS) are used [4]. If the automated warehouse stores pallets, it is called a unit-load AS/RS. If the system is for carton cases or other types of bins, then it is called a mini-load system. In many cases, both types exist in the same distribution center. The products are shipped from the second automated warehouse to retail stores or wholesalers [5].

Investigations into the automated warehouse design problem were mostly with some restrictions such as using only one automated AS/RS. Therefore, an optimal design for the warehouse can be modeled assuming given throughput and capacity limitations, or even a certain capacity is given [6]. In this case, the design is defined by the three dimensions (length, width, and height) and the number of stacker cranes. In practice, two warehouses can exist in the same building with material flow between them, where the first one is for pallets and the second one is for the carton cases. Depalletizers and human depalletizing workers are used to depalletize the pallets and convert them into cases. Then, different cases of different item types are combined together and shipped to each customer. Such a configuration was investigated by only a few studies in the literature [7]. However, a case in which the throughput and capacity of warehouses are the decision variables and not the input variables has been ignored in the literature. The aim of this study is to investigate this gap in research where two warehouses are used and the interaction between them is taken into consideration to avoid sub-optimization approaches. In this study, both throughput and capacity are determined by finding the best lot sizing rules for different classes of products. In the single warehouse problem, which is usually found in the literature, throughput and capacity are inputs. In the new case, in which the two warehouses are investigated simultaneously, the three dimensions of the warehouse must be determined later in the detailed design. Investigating only one warehouse as an isolated system does not guarantee finding the optimal solution. Previous studies generally ignored investigating the two warehouses together due to the complexity of the problem. Companies usually hire some experts in the field to find the "best" design of their distribution centers. However, different experts can give different results based on their guesses and different approaches. Experts might need a long time to provide a solid result. The design planning phase is usually expensive, and changes in a later phase can be very difficult. Therefore, a planning tool that depends on scientific research is needed, and that is the main purpose of this paper. In this paper, the two warehouses are investigated together to find the optimal lot sizing rules of different classes of products for the whole distribution center. These rules affect the throughput and warehouse capacity; and based on the throughput, the number of cranes is determined.

A conceptual design is needed at first. Then, the final exact design is developed by experts. Such a conceptual design, which does not take the exact maximum possible throughput of stacker cranes into consideration is known in the literature. For example, Nikaido [5] assumed two fixed throughputs for the two warehouses. This is because it is extremely complex to consider all the detailed design parameters in two warehouses that are considered together. Sometimes, the whole pallet is not depalletized, especially for low-demand items, to reduce the needed capacity of the second warehouse. Depalletizing the full pallets from the first time will reduce the double handling of pallets in the first warehouse. This double handling comes from the backflow of half full pallets from depalletizers to the first warehouse. In other words, depalletizing the full pallets will decrease the needed throughput of the first warehouse, and therefore lower the number of stacker cranes needed. However, this means that the second warehouse will store more cases than the daily demand. On the other hand, if only the daily demand is depalletized, there will be no double handling, and the capacity in the second warehouse will only be the daily demand, but the double handling will be massive. This tradeoff between the double handling in the first warehouse (and therefore the number of needed stacker cranes) and the needed capacity of the second warehouse is the main concentration of this paper. Therefore, three lot sizing scenarios are investigated in this study to reflect this tradeoff (depalletizing the full pallets, depalletizing only the daily demand, and depalletizing the full layer in a pallet). Different classes of items can have different scenarios. The back flow of materials and the tradeoff between the throughput and the capacity are what make this paper unique. To the best of the authors' knowledge, this paper is the first study that investigates the conceptual design of an integrated storage system containing the two types of warehouses, and considers an efficient approach for investigating the tradeoff between the double handling and capacity of warehouses to minimize the total costs of the system. The methodology of this paper depends on a nonlinear mixed-integer programming model. Most of the contribution of this study is to find the formulas needed to express variables in the model such as throughput and capacity of the two warehouses in different scenarios. Sometimes, formulas are expected to be extremely complicated; therefore, simulation is used instead. The whole tool of the model, formulas, and simulation is performed using MS Excel to be applicable by practitioners of supply chain management. After this introduction, the literature review was conducted to focus on the related studies. Then, the methodology using the nonlinear integer programming model was explained. After that, results and analysis are explained, where discussion about the results is provided. The final section is consists of the conclusions and recommendations for future research.

2. Literature Review

Automation in warehouses has a great impact on the performance of inventory management [8]. The design of the warehouse must consider the policy of inventory management [9]. This is especially important when the capacity of the system plays a vital role. The interaction between inventory management and warehouse management and their environmental impact is considered a significant gap in the literature. Costs and CO_2 emissions are affected by decisions about supply lead times, reorder quantities, and storage equipment [10].

2.1. Material Flow and Warehouse Design

One method to investigate material storage and flow is to study material handling from the internal warehouse to production lines [11]. Another investigation of material flow is the flow in distribution centers, which is the focus of this study. There are several ways to enhance the efficiency of distribution centers and the AS/RS in them [12]. At first, the location of the distribution center can be investigated [13]. Moreover, the smart warehouse management system plays a vital role [14]. In addition, the design of the system provides the greatest opportunity for enhancement. Most of the previous research about warehouse design problem assumed one AS/RS in the facility. The decision is usually to optimize its design based on given throughput and capacity. For example, Karasawa et al. [6] developed a design model for the system of an automated warehouse. The model was formulated as a nonlinear mixed-integer programming problem with the goal of minimizing the system's cost. The decision variables were the number of cranes required, the height of the system, and its length. Ashayeri et al. [15] developed an optimization model for the design of automated warehouses. The objective was to minimize investment and operating costs over the project lifetime. Moreover, Rosenblatt et al. [16] used a different method to investigate the problem of designing AS/RS, where they utilized optimization and simulation model to find the best solution that complies with desired levels of performance. They assumed that the number of stacker cranes can be less than or equal to the number of aisles. Van Oudheusden and Boey [17] investigated the design of an automated warehouse for air cargo that has unique characteristics and needs. Their design was tested using simulation. Some studies considered one aspect of the design such as the study by Lee et al. [18], who investigated the optimal design of rack structure in AS/RS. The best size of modular cell was determined as a decision variable. On the other hand, Lerher et al. [19] investigated, with extensive details, the design problem by minimizing investment cost using genetic algorithms. A comprehensive model of designing the AS/RS for single- and multi-aisle systems was presented. Furthermore, Bortolini et al. [20] investigated the optimal design of AS/RS storage systems with a three-class-based assignment strategy, where they considered the travel time extensively. A new objective which is minimizing CO_2 was introduced in the design problem by Rajković et al. [3]. This is in addition to minimizing costs and travel time. Lewczuk et al. [21] analyzed the energy consumption of a warehouse in various configurations. They presented a method for calculating energy consumption and predicting storage space for each configuration. The costs were also reduced by investigating the path planning problem of AS/RS [22]. Zaerpour et al. [23] proposed a decision tool for selecting the appropriate type of storage system that minimizes investment and operational costs while meeting warehouse design requirements, specifically storage capacity and throughput.

In most of the previous studies, a unit-load AS/RS, which is used for pallets, was assumed. On the other hand, the study by Bozer and White [24] concentrated on designing the mini-load system used for cases or bins, where the system can be described as an end-of-aisle order picking system. The objective of the design algorithm was to minimize the number of storage aisles subject to two types of capacity constraints: throughput and storage space. Then, Bozer and White [25] continued their work and developed an analytical design algorithm to determine the near-minimum number of pickers required in an end-of-aisle order picking operation. The study estimated the expected picker utilization (and the storage/retrieval machine utilization). That means that the previously mentioned studies investigated the design for one unit-load AS/RS or one mini-load AS/RS.

Another limitation in the previously mentioned studies is that the needed size of storage was assumed to be an input for the model. Some studies, however, investigated the size as a decision variable such as the study by Cormier and Gunn [26], which investigated the optimal warehouse size. Before that, Rosenblatt and Roll [27] investigated the factors that influence a warehouse's required capacity in a stochastic environment. A simulation model was developed to assess the relationship between warehouse capacity and the various relevant parameters. They discovered that the required capacity is primarily influenced by the number of items stored, the ordering quantity, and the average number of items issued per day. Moreover, Shi et al. [28] investigated dynamic warehouse size planning. Before the planning horizon begins, a manager announces the nominal size of the warehouse space to rent (strategic decision), and during the horizon, the ordering quantity and actual warehouse size are determined (operational decision).

2.2. Two Warehouses Design Problem

Among the early attempts to include two warehouses in the system was the study by Dessouky and Wilson [29], who developed a robotic assembly system that is integrated with an AS/RS. There are depalletizer robots and assembly robots. The objective was to minimize production costs for the robotic assembly system. Only a few studies investigated the material flow system containing both unit-load and mini-load AS/RS. For example, Yasunaga et al. [30] developed a design algorithm for logistics networks. The problem was divided into two parts: material flow and layout planning, and a mixed-integer problem was used. They assumed the existence of two automated warehouses and depalletizer. The focus was to shorten the lead time, which is the time elapsed between the order and shipping. Moreover, Nikaido et al. [5] developed a conceptual warehouse design algorithm using the mixed-integer linear programming problem. They classified the products into two categories: those in high demand (A-ranked products) and those in low demand (B-ranked products). The threshold used to divide the product was considered as among the decision variables. However, they did not consider different levels of lot size. That means for all types of pallets, the whole pallet is depalletized at once, hence there is no back flow of materials. Furthermore, a study by Nikaido et al. [7] proposed a flow design method for an automated distribution center with multiple shipping areas. They considered the main design elements to be the number of devices and the volume of product flow between the devices. However, the tradeoff between the throughput and storage capacity was not investigated in their study. Ozaki et al. [31] investigated the design of warehouse using queuing network theory. They assumed using automated pallet storage, a depalletizer, and AS/RS with a sorting system for cases, and their model was proposed to calculate the temporary storage area.

2.3. Double Handling and Study Contribution

The reversed movement of pallets, which leads to double handling in warehouses, is known in the literature. Double handling occurs when the daily demand is less than the pallet size, and the decision is made to take only some of the carton cases from the pallet (using depalletizers), and keep the rest in the unit-load warehouse until the rest of cases are needed. Bringing the same pallet to the depalletizers two times or more will increase the needed throughput, but can save the needed storage space in the mini-load warehouse. For example, Chen et al. [32] investigated a situation in which the amount of a certain item retrieved is less than a pallet load. The re-assigning process of the storage locations of nonempty pallets after each retrieval was considered by that study. The demand for less than a pallet load was also investigated by the study by Alnahhal et al. [33]. However, the effect of double handling on the design problem of AS/RS was ignored in the literature. This study investigates this gap in research. All the previous studies totally ignored the effect of lot size strategy on both the needed throughput and capacity. The throughput was always assumed to be an input parameter. The tradeoff between throughput and size was ignored. Therefore, the contribution of this study is to present a new investigation method based on practical configurations, to find the conceptual design of the whole system to reduce the total costs. This conceptual design is determined by finding the best combinations of lot sizing rules for different classes of products. The costs include investment costs of stacker cranes in both warehouses, their maintenance, and storage capacity costs. This is achieved based on the detailed demand for each class of products (A, B, and C). The data used are assumed based on the authors' experience. This study finally results in a tool to help decision makers find the best solution based on analytical formulas, simulation, and the model using them. Some experts in the field were asked to review the proposed methodology to give their feedback on its logic and assumptions. Positive feedback was given by these experts.

3. Methodology

The focus of this research is to find the best lot sizing rules (scenarios) that affect doubling handling and needed capacity in distribution centers. The number of sacker cranes is defined by the level of double handling. The size of the two warehouses and the number of stacker cranes are the design components of this study. Based on these design components, the total cost is computed. The exact length and height of the warehouse were not investigated, because they are assumed to be found in a later stage of the final design. In detailed design, which is not the main focus of this study, other details must be determined such as the number of bays, the number of levels, slots in particular aisles, and the length of the racking rows. Products are received in pallets at the distribution centers and shipped in accordance with orders from retailers and wholesalers. The flowing materials are pallets and cases. The system can be illustrated as in Figure 1. The assumed system contains two AS/RS systems and depalletizers. There is one AS/RS for pallets (unit-load or WH1) and one AS/RS for cases (mini-load or WH2). Usually there are palletizers after the mini-load system to reattach the cases from different types. The new mixed pallets are then shipped to the customers. Both 'D' and 'd' are the demand in pallets and cases, respectively, and they are independent from the lot sizing strategy used. However, the output pallets (PL_o) moved to the depalletizer and the reversed half full pallets (HPL_I) depend on the strategy used. The strategy will determine if the lot size will cover only the daily demand or more. More HPL_I means more double handling. If only demand is moved forward, the rest of the pallet will come back again to WH1 again. The objective is to reduce the total costs of the system. The costs are for the storage location space in two warehouses and the number of stacker cranes including the maintenance costs of them. Different lot sizing rules can be used for different classes of materials. An MS Excel tool has been designed for this study. The tool contains both the formulas and the simulation analysis. The simulations needed in the conceptual design are simple and static, and therefore did not map the operating dynamics of the stacker cranes. Therefore, simulation did not consider parameters such as the stacker cranes accelerations, double cycles, or different jobs assignments. This tool can be used by decision makers to determine the optimal solution. Generally, providing the formula for the capacity or throughput, whenever possible, is better to generalize the investigation, and make the study applicable for other parameters values. However, sometimes the formula is difficult to obtain due to the complexity of the system. In this case, simulation is used.

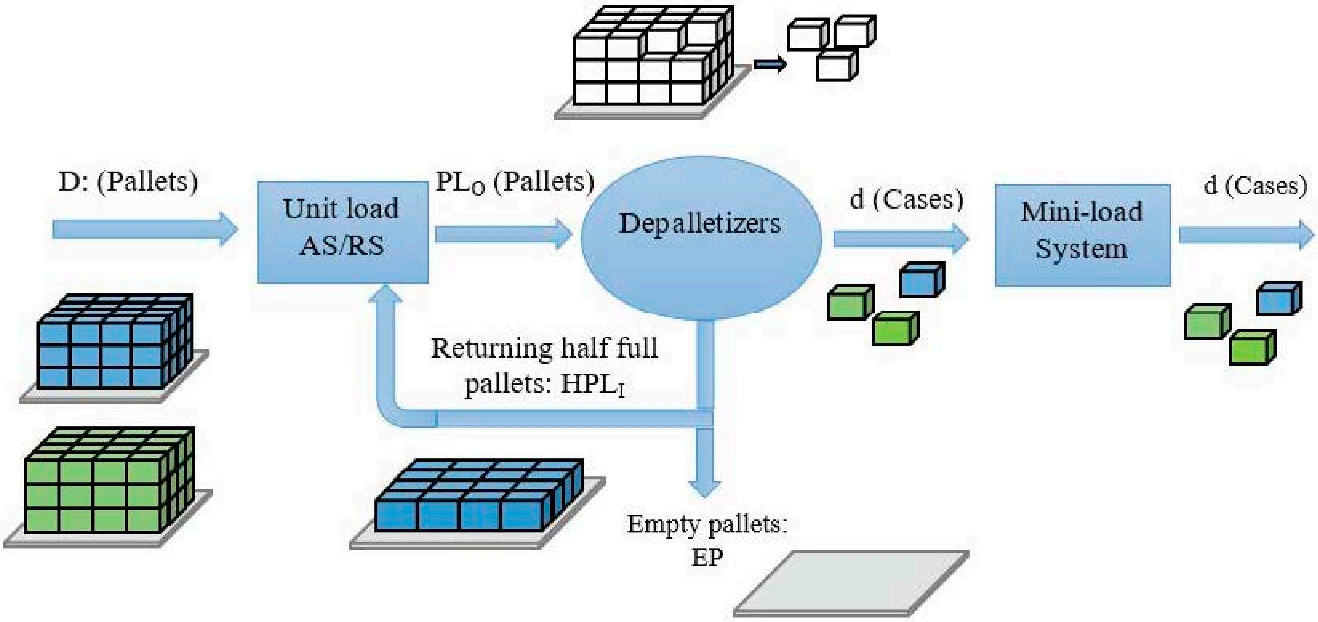

Figure 1. Material flow diagram.

Generally, simulation has the limitation that it provides the results for some particular input parameters. To deal with this limitation, the use of simulation was only kept for checking the accuracy of the formulas and when the system is complex, and finding a formula seems very difficult. In most of such situations, some approximation equations were found from the simulation results to describe a wide range of inputs such as different average daily demand. Later in this paper, situations for which simulation was used will be identified. Equations describing a wide range of parameters will also be provided.

3.1. Study Scenarios and Assumptions

There are three different situations for the size of the daily demand:

1. Daily demand is less than a layer size (assumed to be C items in this study);
2. Daily demand is equal to or greater than a layer size, but less than or equal to a pallet size (assumed to be B items in this study);
3. Daily demand is greater than pallet size (assumed to be A items in this study).

ABC analysis is widely used in the literature and in practice, where A items are used every day and in large quantities. C items are rarely consumed, and B items are in-between. Usually different movement rules are used for different classes of items. For the above classes of items, there are three different scenarios of lot sizing:

1. Scenario 1 (daily demand): Only the daily demand is depalletized and moved to the mini-load system.
2. Scenario 2 (full layers): Lot size is an integer number of pallet layer. For example, if the current demand is 7 cases, and each layer is 5 cases, then 10 cases (two layers) must be depalletized and moved to the mini-load system.
3. Scenario 3 (full pallets): Whole pallets are depalletized. For example, if the demand is 60 cases, and the pallet size is 50 cases, then two pallets must be depalletized and sent to the mini-load system.

In the first scenario, the needed capacity of WH2 is reduced to be only the daily demand, and the increase is on the needed throughput of WH1. More throughput means increasing the number of needed stacker cranes, which are very expensive and need maintenance. On the other hand, scenario 3 reduces the throughput to the minimum possible level, where there are no any moving half full pallets. However, because whole pallets are depalletized at once and sent to WH2, the needed capacity of WH2 increases. Scenario 2 tries to be in the middle of the other two scenarios. The optimal scenario in this study is the flexible scenario in which different classes of items (A, B, and C) can be assigned to different scenarios from the above ones. Applying the right scenario for the right items class is the decision to be made in this paper based on the total costs of the system (see Figure 2). The second and third scenarios provide the advantage of responding quickly to customer demand because of the storage buffer in WH2. If the time between ordering and shipping is short, a large amount of stock in WH2 is required.

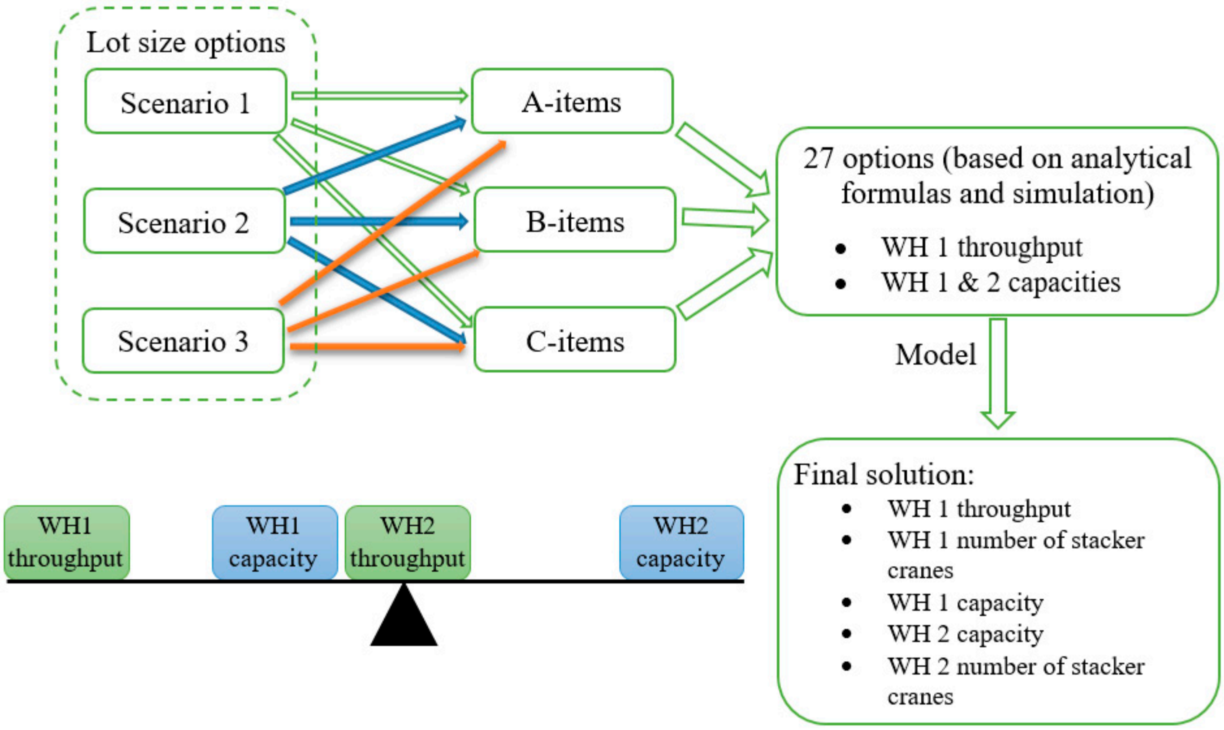

Figure 2. Determining design parameters based on scenarios and class of items.

The average throughput for the mini-load system is always the same, regardless of the scenario used. However, the throughput of the unit-load AS/RS is different based on different scenarios. This is because the throughput is measured in this case based on the movement of pallets, into and out of WH1. These pallets are not always full, and in many cases are moved to the depalletizers where some cases are taken to WH2, and the pallets that are left are returned to WH1 to meet the demand for the next few days. Therefore, the concentration in this paper will be on an efficient method to select the configuration of such movements. The capacity needed is also affected by the strategy used. The effect on the capacity is more obvious for the mini-load system, as will be shown later. Different values for WH1 throughput and the capacity of both warehouses depend on the size of daily demand and the scenario used. Figure 2 shows how to determine the different design parameters (throughput and capacity). WH1 throughput and WH1 capacity and WH2 capacity are the important factors to be found for each scenario for each class of items (all of them are 27 options). This is because the throughput of WH2 is always fixed to be the daily demand. The lower left side of the figure shows the nature of tradeoff between two warehouses' capacity and throughput. WH2 throughput is in the middle, meaning that it is always fixed. Whenever the throughput of WH1 increases (as in scenario 1), the capacity of WH1 increases slightly, but the capacity of WH2 decreases. The slight reaction by the WH1 capacity is because the pallet size contains many cases. This increase is due to the returning pallets to WH1 after depalletizing some of the cases of these pallets. For decision makers, the decision to be made is which lot sizing rule should be used for each class of products; and these rules will eventually affect the following design components:

- The capacity of the mini-load system;
- The capacity of the unit-load AS/RS (the first warehouse);
- The level of double handling in the first warehouse, which defines the warehouse throughput (the daily demand also affects the throughput);

The number of stacker cranes for the unit-load AS/RS (based on the throughput).

When the real demand is more than the expected demand, in scenarios 2 and 3, there are usually more carton cases in the second warehouse than the average demand. These extra cases can be used to satisfy any sudden unexpected increase in the demand. However, in scenario 1, if the expected daily demand is moved, and an order comes after this movement with demand that is more than expected, then more cases are needed (follow-up throughput). To deal with such a problem, the following techniques can be considered:

1. Try not to use the first scenario for C items.
2. If scenario 1 is to be used for C items, it is better to wait until the order comes, and then cases are shipped directly without going to the second warehouse.
3. If a new order for a C item comes after the first shipment in the same day, then there should be some safety stock in the second warehouse, and the extra demand is satisfied from this safety stock.

The following assumptions are made:

- The depalletized cases must cover at least the daily demand. In other words, the daily demand is not very large to the level it needs to be divided into several lot sizes every day.
- Before commencing the retrieval order from the first warehouse, the total daily demand for an item by all customers can be known with reasonable accuracy. Pooling the demand by all the customers can reduce the fluctuations of the demand for that item.
- Pallets come in only one size (measured in number of cases).
- Average service time for stacker cranes in each warehouse was assumed to be known.
- The variability in the total number of daily active items is not very high. Active items today are the items needed today.
- The new batch of cases of a certain item will come to the mini-load system just in time, when the old cases are consumed.
- Cross docking, in which full pallets are transshipped directly to the customer from the first warehouse, is not considered in this study.
- In reality, when an order comes for an item that is currently in the depalletizer, cases of that item can be shipped without being stored in the second warehouse. Therefore, there is no need for the capacity of the cases of that item on the second warehouse. This fact was ignored in this paper because of the dynamic nature of demand and in order to provide more buffer of capacity in the second warehouse. In other words, this capacity may be required for safety stock in order to hedge against demand uncertainty. The best safety stock level can be investigated in future research.
- The maximum inventory level (T) in the system is given. This maximum value contains the inventory in both warehouses. It should cover the demand for a certain number of days. Different classes of items can have different coverage periods. T-value can be the order quantity (Q) plus the safety stock (SS). The Q-value depends on factors such as lead time, minimum size of shipment, and setup costs. The safety stock level is also given. The total capacity of two warehouses is not exactly as the total inventory because the capacity should cover the maximum value in the beginning and the end of the day. That might also lead to different total capacity for different scenarios.

Table 1 shows the known and calculated parameters. The approach in this paper can be applied for any data with the same assumptions. Based on the basic known parameters, the calculated parameters are found using the given formulas.

Table 1. Known parameters, calculated parameters, and model decision variables.

Symbol	Meaning	Value	Unit	Formula (If Any)
	A. Basic known parameters			
PL_c	Pallet size	50	cases	
I_d	Different number of active items in one day	1000	item types	
d	Average daily demand of all items	10,000	cases/day	
I_A	Percent of number of different A items	10	%	
I_B	Percent of number of different B items	20	%	
I_C	Percent of number of different C items	70	%	
V_A	Percent of demand volume for A items	70	%	
V_B	Percent of demand volume for B items	20	%	
V_C	Percent of demand volume for C items	10	%	
N_L	Number of layers per pallet	10	layers	
A_c	Percent of daily active C items	33.33	%	
	B. Input parameters for the cost model			
M_{t1}	WH 1 maximum throughput per aisle	50	PL/hour	
M_{t2}	WH 2 maximum throughput per aisle	200	case/hour	
S_{c1}	WH 1 stacker crane cost	350,000	dollar	
S_{c2}	WH 2 stacker crane cost	250,000	dollar	
L_{c1}	WH 1 storage location cost	150	dollar	
L_{c2}	WH 2 storage location cost	30	dollar	
M_c	Maintenance cost %	5	%	
W_p	Working period	20	years	
d_f	Discount factor	0.2		
	C. Calculated parameters			
D	Daily demand in pallets	200	pallets	d/PL_c
D_A	Daily demand in pallets of class A items	140	pallets	V_A D
D_B	Daily demand in pallets of class B items	40	pallets	V_B D
D_C	Daily demand in pallets of class C items	20	pallets	V_C D
N_A	Number of different A items	100	item types	I_d I_A
N_B	Number of different B items	200	item types	I_d I_B
N_C	Number of different C items in one day	700	item types	I_d I_C
d_A	Daily demand (in cases) of class A	7000	cases	d V_A
d_B	Daily demand (in cases) of class B	2000	cases	d V_B
d_C	Daily demand (in cases) of class C	1000	cases	d V_C
PPI_A	Daily demand per item of class A	1.4	pallets per item	N_A/D_A
PPI_B	Daily demand per item of class B	0.2	pallets per item	N_B/D_B
PPI_C	Daily demand per item of class C	0.03	pallets per item	N_C/D_C
L_s	Layer size	5	cases per layer	PL_c/N_L
TN_C	Total number of different C items	2100	cases	N_C/A_c

Table 1. *Cont.*

Symbol	Meaning	Value	Unit	Formula (If Any)
	D. Model decision variables			
Y_1 and Y_2	Number of stacker cranes in WH1 and WH2			Equations (15) and (16)
Cap1	WH1 capacity		storage locations (Pallets)	Equation (22)
Cap2	WH2 capacity		storage locations (cases)	Equation (28)
$Cap2_{xi}$	Needed capacity of WH2 for x items based on scenario i		cases	Equations (26) and (27)
Th1	WH1 throughput		PL/day	Equation (24)
$Th1_i$	Total WH1 throughput if scenario i is used		PL/day	Equations (8), (13) and (14)
$Th1_{xi}$	WH1 throughput for x items if scenario i is used		PL/day	Part of $Th1_i$ or Simulation
SCC	Storage capacity cost		dollar	Equation (18)
TMC	Total maintenance costs		dollar	Equation (17)
TC	Total costs		dollar	Equation (19)

The values of M_{t1} and M_{t2} were assumed to be fixed in the table for simplicity in the conceptual design; however, the exact capacities of the stacker cranes depend on the length, the height of the racks, the number of storage locations in each aisle, the uneven (or not) distribution of the tasks among the aisles, and the possibility of using double cycles by the stacker cranes. The unit-load AS/RS capacity depends on Q and SS values. Simulation was used in this study to find the WH1 capacity for different scenarios as will be shown later in the section of results and analysis. The needed capacity for WH2 is independent from the Q and SS values, and it depends on the demand and the scenario used.

3.2. Scenario 1

In each scenario, both the WH1 throughput and the WH2 capacity are investigated, and based on them, the other design parameters are determined. WH1 capacity will be found based on simulation. In scenario 1, it is assumed that only the daily demand is depalletized and moved to the mini-load system. In this scenario, PL_O is much larger than D. This is because that not all of the pallets coming out of the unit-load AS/RS are full. The total throughput for the unit-load AS/RS is the total storage and retrieval movements for the A, B, and C classes of items, which can be found as follows:

$$Th1 = D_A + PL_{OA} + HPL_{IA} + D_B + PL_{OB} + HPL_{IB} + D_C + PL_{OC} + HPL_{IC} \quad (1)$$

The values for PL_O and HPL_I depend on the size of the daily demand. The reverse movement (HPL_I) represents the double handling of pallets. The values for D_A, D_B, and D_C are given in Table 1.

3.2.1. WH1 Throughput When Daily Demand Is Less Than One Pallet

If the average daily demand is less than the pallet size for a certain item, then the number of moving pallets from the unit-load AS/RS to the depalletizer (PL_O) depends on the number of different item types and the daily demand per item. When the half-full pallet in the unit-load AS/RS is insufficient, a new pallet must be opened (NPO). If the average daily demand for that item is 20% of the pallet size, this NPO occurs every 5 days, except when the total demand of the five days is exactly 100% of the pallet size. The probability of obtaining such a volume is usually small. Therefore, we can assume it to be zero to simplify the formula. In other words, if we assume that the PPI_B and PPI_C are less than 1, then:

$$PL_{OB} = N_B + N_B PPI_B \quad (2)$$

$$PL_{OC} = N_C + N_C PPI_C \quad (3)$$

Most of the time, the opened pallet will return to the unit-load AS/RS, and therefore the number of half full pallets returning to the WH1 can be approximated to be

$$HPL_{IB} = N_B \quad (4)$$

$$HPL_{IC} = N_C \quad (5)$$

The difference between PL_O and HPL_I represents the empty pallets.

3.2.2. Throughput When Daily Demand Is Greater Than One Pallet

For the value PL_{OA}+ HPL_{IA}, when the daily demand for a certain item is more than one pallet, a different approach must be followed. In this case, the number of full pallets leaving the unit-load AS/RS (PL_{OAF}) equals the number of different items multiplied by the lower rounding of the average daily demand per item ($PPI_A\ N_A$). If the daily demand is greater than 2 pallets for example, then the number of different items must multiplied by 2. The half full pallets moving out the unit-load AS/RS (PL_{OAH}) are two types. The first one is already opened from a previous day, and second type is the new opened ones. The first type occurs almost every day for each item, and therefore we can assume it will be as the number of different items (N_A). The frequency of the second type can be found by taking the last digits of the daily demand and multiplying them by the number of different types ($N_A\ (PPI_A - PPI_A)$). Therefore, the total number of moving pallets out the unit-load AS/RS is

$$PL_{OA} = PPI_A\ N_A + N_A + N_A\ (PPI_A - PPI_A)$$

Which can be rewritten to be as follows

$$PL_{OA} = N_A[1 + \ PPI_A] \quad (6)$$

Since in most of the days there are returning pallets, the HPL_{IA} can be assumed to be as the number of different items. Therefore, it is possible to write

$$PL_{OA} + HPL_{IA} = N_A[2 + \ PPI_A] \quad (7)$$

When the average daily demand for a certain item is close to the pallet size, sometimes the number of full pallets exiting the unit-load AS/RS will be zero, but in this case, a new opened pallets occurs, and therefore the formula representing the total number of movements can be kept as it is. To check the accuracy of the formula above, simulation was used. Results of the simulation are presented later only when formulas are not developed in this section. The formula in Equation (1) can be rewritten to be as follows

$$Th1_1 = D_A + N_A[2 + PPI_A] + D_B + 2N_B + N_B PPI_B + D_C + 2N_C + N_C PPI_C \quad (8)$$

The throughput for A items was measured using Formula (7). Formulas (2)–(5) are used for throughput of B and C items. The terms D_A, D_B, and D_C were added to represent the entering pallets from the suppliers.

3.2.3. Capacity of the Mini-Load System

The capacity of WH1 in all scenarios is determined in paper using simulation. The total needed capacity of the mini-load system will be the daily demand (d) plus some safety capacity. This is because only the daily demand will reach WH2. The safety capacity might be needed for any fluctuation in demand.

3.3. Scenario 2

In this case, full layers are depalletized and moved.

3.3.1. Throughput When Daily Demand Is Greater Than One Pallet

The previous formula (Equation (7)) cannot be applied here, because the depalletized layers will increase the chance of satisfying the demand without the need for a new opened pallet, and therefore reduce the number of half full pallets. Simulation can be used to estimate the throughput as shown in the results and analysis section.

3.3.2. Throughput When Daily Demand Is Less Than One Pallet

Equations (2) and (3) will not be suitable for this case, because the number of second opened pallets, NPO, will be decreased because of moving layers instead of cases. When the layer size is smaller than the average daily demand, it was found using simulation that the value of the previous formula is reduced by approximately the ratio of layer size to the pallet size multiplied by the number of different items. Therefore, the new formula can be as follows:

$$PL_{OB} = N_B + N_B PPI_B - \frac{N_B L_S}{PL_C} = N_B\left(1 + PPI_B - \frac{1}{N_L}\right) \quad (9)$$

When the size of the layer is greater than the average daily demand of the item as assumed for C items, the equation will be

$$PL_{OC} = \frac{N_C PPI_C PL_C}{L_S} + 0.5 N_C PPI_C \quad (10)$$

where the first term of the equation represents the old opened pallets, and the second term represents the new opened pallets. The above equation is an approximation which was tested using simulation. It is also possible to write:

$$HPL_{IB} = PL_{OB} - D_B \quad (11)$$

$$HPL_{IC} = PL_{OC} - D_C \quad (12)$$

As obvious, the variables (PL_O) and (HPL_I) in Formulas (9)–(12) are less than the variables in Formulas (2)–(5), which are for scenario 1.

The total WH1 throughput for scenario 2 can be written as follows

$$Th1_2 = D_A + PL_{OA} + HPL_{IA} + 2N_B\left(1 + PPI_B - \frac{1}{N_L}\right) + \frac{2N_C PPI_C PL_C}{L_s} + N_C PPI_C \quad (13)$$

To find the complete calculations of $D_A + PL_{OA} + HPL_{IA}$, results of the simulation must be obtained at first as in the results and analysis section. Even though the throughput in this case can be estimated using formulas without the need for simulation, using simulation can be useful to compare the formulas with the results of simulation. Table 2 shows how to find the needed throughput for class B (scenario 2) for 10 days. To obtain accurate results, 1000 days were used. Demand was assumed to be Poisson distributed. Four columns are needed to track the throughput. There were no full pallets moved because the demand was assumed to be 10 cases (20% of the pallet size). There are two columns for the half pallets. Column (2) is for the pallets which were reassigned again to WH1. Then, they are needed again to satisfy the demand. The demand of the first six days consumes the first pallet plus 20% of a new pallet. Column (3) is for the pallets that are opened for the first time, but only some of the cases in the pallet are needed. On day 6, 20% of the pallet is used. The left 80% goes back to WH1 again. On day 7, only 10% of the pallet is used, and therefore 70% goes back again to WH1. This cycle continues until the end of the simulation. The output pallets (PL_O) is computed by counting how many nonzero in the columns (1), (2), and (3). The reversed moving pallets (HPL_I) is computed by counting how many nonzero in column (4). The throughput is the summation of both of them plus the entering pallets to WH1 from suppliers. The summation of the "total handling (PL)" column represents these entering pallets.

Table 2. Simulation using Excel for WH1 throughput of B items (scenario 2).

Day	Random "d"	Accumulated "d"	Round Up	Lot Size	Total Handling (PL)	Throughput				Empty Pallets
						Full Pallet (1)	First Half Pallet (2)	Second Half Pallet (3)	Reverse Pallet Size (4)	
1	9	9	10	10	0.2	0	0.2	0	0.8	0
2	10	19	20	10	0.4	0	0.2	0	0.6	0
3	14	33	35	15	0.7	0	0.3	0	0.3	0
4	7	40	40	5	0.8	0	0.1	0	0.2	0
5	5	45	45	5	0.9	0	0.1	0	0.1	0
6	11	56	60	15	1.2	0	0.1	0.2	0.8	1
7	7	63	65	5	1.3	0	0.1	0	0.7	0
8	15	78	80	15	1.6	0	0.3	0	0.4	0
9	13	91	95	15	1.9	0	0.3	0	0.1	0
10	11	102	105	10	2.1	0	0.1	0.1	0.9	1

The calculations for WH2 capacity for B items will be shown later. However, stochastic demand was used to find the needed WH2 capacities. The simulation used was added in the same Excel file containing the equations so that decision makers of distribution centers can use both formulas and simulation easily.

3.3.3. Capacity of the Mini-Load System

It was found using simulation that the capacity is exactly as the daily demand if the daily demand is greater than the layer size, such as the situation for A and B items. In this case, some lot sizes will be higher than the average demand and others are lower than it. On the other hand, if the daily demand is less than the layer size (C items), then the needed capacity of the mini-load system is more than the average daily demand. In this case, simulation is needed to find the capacity of WH2 for C items. Therefore, in scenario 2, WH1 throughput of A items and WH2 capacity of C items are found using simulation.

3.4. Scenario 3

In this scenario complete pallets are depalletized.

3.4.1. Throughput of WH1

For the three classes of items, the throughput is exactly as the daily demand in pallets. This is because only full pallets are moving to depalletizers, with no return movements to the unit-load AS/RS. However, these pallets move at first to WH1 and then from it to the depalletizers. Therefore, the daily demand is multiplied by 2. Therefore, the total throughput can be written as follows

$$Th1_3 = 2D \quad (14)$$

3.4.2. Capacity of the Mini-Load System

Since the demand for A items is usually greater than the pallet size, the needed capacity is exactly as the daily demand, plus some safety capacity if needed. For B items and C items, simulation is needed to find the needed capacity as will be shown in the results and analysis section. Table 3 shows when it is possible to analytically obtain the values of WH1 throughput and WH2 needed capacity, and when it is difficult to obtain a formula, and therefore simulation is needed. In such cases, an approximation formula can be obtained from the simulation. As obvious from Table 3, simulation was only used to find four variables of capacity and throughput from the 18 variables needed to be identified. Later in the next section, approximation formulas that cover a wide range of parameters will be found for three of these four variables. The only variable that needs to be estimated using simulation, every time there is a change in the demand, is the WH2 capacity for C items. A formula for this situation in future research would be very helpful. Table 3, however, does not show the WH1 capacity which was found using simulation.

Table 3. Methods used to determine the WH1 throughput and WH2 capacity.

	Scenario 1		Scenario 2		Scenario 3	
Item	**WH 1 Throughput**	**WH 2 Capacity**	**WH 1 Throughput**	**WH 2 Capacity**	**WH 1 Throughput**	**WH 2 Capacity**
A	Formula	Formula	Simulation	Formula	Formula	Formula
B	Formula	Formula	Formula	Formula	Formula	Simulation
C	Formula	Formula	Formula	Simulation	Formula	Simulation

3.5. Costs Model

The costs model depends on the given data in the second part of Table 1.

The number of the stacker cranes (Y_1 for WH1 and Y_2 for WH2) is found based on the needed throughput and the capacity for each stacker crane (M_{t1} for stacker cranes in WH1 and M_{t2} for stacker cranes in WH2).

$$Y_1 = Th1/8M_{t1} \tag{15}$$

$$Y_2 = Th2/8M_{t2} = 2d/8M_{t2} \tag{16}$$

Y_2 is fixed regardless of the scenario used. This is because it depends on the throughput of WH2, which depends directly on the daily demand, and has nothing to do with double handling of pallets as in WH1. The throughput of WH1 is determined based on Equation (1). The maintenance costs can be found as follows

$$TMC = M_c\ (S_{c1}\ Y_1 + S_{c2}\ Y_2) \sum_{i=1}^{W_p} \left(1 + d_f\right)^{-i} \tag{17}$$

The use of the discount factor for maintenance of stacker cranes is known in the literature [15]. The term before the summation is the maintenance cost for one year. The costs for storage capacity requirements can be found as follows

$$SCC = L_{c1}\ \ Cap1 + L_{c2}\ \ Cap2 \tag{18}$$

The total costs (TC) will be as follows

$$TC = S_{c1}\ Y_1 + S_{c2}\lceil 2d/M_{t2}\rceil + M_c\ (S_{c1}\ Y_1 + S_{c2}\lceil 2d/M_{t2}\rceil) \sum_{i=1}^{W_p} (1 + d_f)^{-i} + Cap1\ L_{c1} + \ Cap2\ \ L_{c2} \tag{19}$$

Equation (19) is a function of Y_1, WH1 capacity, and WH2 capacity. Assume that X_{Ai}, X_{Bi}, and X_{Ci} are defined as follows

$$X_{Ai} = \begin{cases} 1\,, & if\ A\ items\ are\ depalletized\ according\ to\ scenario\ i \\ 0, & otherwise \end{cases}$$
$$X_{Bi} = \begin{cases} 1\,, & if\ B\ items\ are\ depalletized\ according\ to\ scenario\ i \\ 0, & otherwise \end{cases}$$
$$X_{Ci} = \begin{cases} 1\,, & if\ C\ items\ are\ depalletized\ according\ to\ scenario\ i \\ 0, & otherwise \end{cases}$$

where i has the values 1, 2, and 3, representing the three different scenarios of lot sizing rules. There are 27 different combinations of such variables. The optimal solution is found after trying all the 27 combinations using simple numerations. Throughput of WH1 is as follows

$$\begin{aligned} Th1 = (D_A + N_A[2 \quad & +PPI_A])X_{A1} + (D_B + 2N_B + N_B PPI_B)X_{B1} \\ & +(D_C + 2N_C + N_C PPI_C)X_{C1} + Th1_{A2}X_{A2} \\ & +t(2N_B(1 + PPI_B - \tfrac{1}{N_L}))X_{B2} + (\tfrac{2N_C PPI_C PL_c}{L_s} + N_C PPI_C)X_{C2} \\ & +2D_A X_{A3} + 2D_B X_{B3} + 2D_C X_{C3} \end{aligned} \tag{20}$$

The formula of $Th1_{A2}$ will be found by simulation in the next section. Equation (20) should be used to find the value of Y_1 as in Equation (15). Then, this value is used in Equation (20). The other design parameter is defined as follows

$$\begin{aligned} Cap2 = d_A X_{A1} + d_B X_{B1} + d_C X_{C1} + d_A X_{A2} + d_B X_{B2} + Cap2_{c2}X_{C2} + d_A X_{A3} \\ +\mathrm{Cap2}_{B3}X_{B3} + \mathrm{Cap2}_{C3}\ X_{C3} \end{aligned} \tag{21}$$

So far, three values of the needed capacity are still unknown, and they will be found using simulation in the next section. Equation (21) can be used directly in (19).

$$\begin{aligned} Cap1 = N_A C_{A1} X_{A1} + N_B C_{B1} X_{B1} + TN_C C_{C1} X_{C1} + N_A C_{A2} X_{A2} + N_B C_{B2} X_{B2} \\ +TN_C C_{C2} X_{C2} + N_A C_3 X_{A3} + \mathrm{N}_B C_{B3} X_{B3} + \mathrm{TN}_C C_{B3}\ X_{C3} \end{aligned} \tag{22}$$

where C_{ij} means the needed capacity in WH1 allocated for "i" items based on "j" scenario. The nonlinear integer programming model has the objective function of TC defined in Equation (19). The constraints are Equations (15) and (20) used to define Y_1; Equation (21) to define WH2 capacity; and Equation (22) to define WH1 capacity. However, later in the next section Equation (21) can be rewritten to include $Cap2_{C2}$ and $Cap2_{B3}$ based on the insights from simulation as in Equation (28). Moreover, Equation (20) can be rewritten as in Equation (24) in the next section to include the value of $Th1_{A2}$ found based on simulation. The three variables $Cap2_{C2}$, $Cap2_{B3}$ and $Th1_{A2}$ were difficult to find based on analytical investigation. Therefore, simulation was used to define them. The previous equations from (1) to (14) and from (16) to (18) are included in the nonlinear integer model (OF defined in (19), and constraints defined in (15), (20), (21), and (22)). The results of the model are based on the values found using the shown formulas, except when there is a need for simulation for some variables. In this case, the average values of simulation results are used.

4. Results and Analysis

Using simulation, Table 4 shows the average needed capacity per item in warehouse 1 in pallets (PL), associated with the assumed Q and SS values. The results in Table 4 can be different for different parameters. Therefore, future research can investigate finding exact or approximation formulas. However, as expected from Figure 2, the differences in the needed WH1 capacity for different scenarios is not so big, and small changes on the input parameters can be negligible. The first two scenarios in Table 4 have almost the same results. The biggest difference in the capacity requirements is for C items when scenario 3 is used. However, later in this paper, we will see that it is better not to use scenario 3 for C item. Therefore, the concentration in this paper is on WH2 capacity requirements.

Table 4. Average needed capacity per item in WH1 for different scenarios.

Item Class	Scenario 1	Scenario 2	Scenario 3
A (Q = 5 PL, SS =2 PL)	6.4	6.4	5.54
B (Q = 2 PL, SS =1 PL)	2.5	2.5	1.6
C (Q = 1 PL, SS =1 PL)	2	1.94	1

The given Q and SS were assumed so that they cover the demand for at least 5 days. Different results can be obtained for different values of them. Finding the optimal value of Q and SS is not in the scope of this study. Scenario 3 tends to need lower capacity per item in WH1, because there is no half pallets kept in WH1 in that scenario. This section will also present the results of the simulation models generated to find values whenever formulas are difficult to obtain. Then, the results based on the analytical equations and the simulation are presented. Finally, the optimal solution is found from the 27 options provided later. Since the capacity of WH1 is already found in the previous table using simulation, the concentration starting from now is on WH2 capacity.

4.1. Scenario 1

There is no need for simulation in this scenario because all the values are obtained using formulas. Table 5 shows the summary of the calculations for scenario 1 in its first part. The values of N, D, d, and PPI for A, B, and C items are in Table 1. The calculations in Table 5 depend on these input values. The last two columns show the throughput of WH1 and needed capacity of WH2. The WH2 capacity is exactly as the daily demand for scenario 1.

Table 5. Calculations of WH 1 throughput and WH2 capacity for the three scenarios.

Item	PL_O	HPL_I	Th1 (PLO + HPL_I + D)	Cap2
A. Scenario 1				
A	240	100	480	7000
B	240	200	480	2000
C	720	700	1440	1000
Total			2447	10,000
B. Scenario 2				
A	323 *		463	7000
B	220	180	440	2000
C	210	190	420	6720 *
Total			1323	15,720
C. Scenario 3				
A	140	0	280	7000
B	40	0	80	6000 *
C	20	0	40	54,600 *
Total			400	67,600

* Simulation results.

4.2. Scenario 2: Simulation for WH1 Throughput of A Items

Simulation is used because there was no formula provided in this study for A items throughput. The average daily demand of that item was assumed to be 1.4 pallets. The daily demand is different every day based on a Poisson distribution. MS Excel was used to generate random numbers and run the simulation until 1000 days. Results of the out full (PL_{OAF}) and half full (PL_{OAH}) movements of WH1 were obtained for one item. The in WH1 movements (HPL_{IA}) were also obtained. Figure 3 shows the ratio between output and input pallets ($R_{IOA} = (PL_{OA} + HPL_{IA})/D_A$) for WH1 when the full layers are depalletized. According to the ratio found, the throughput is $D_A\ R_{IOA} + D_A = 140 \times 2.31 + 140 = 463$. Figure 3 is useful to cover the simulation results of different average demand values. The ratio R_{IOA} is used to find the WH 1 throughput of A items.

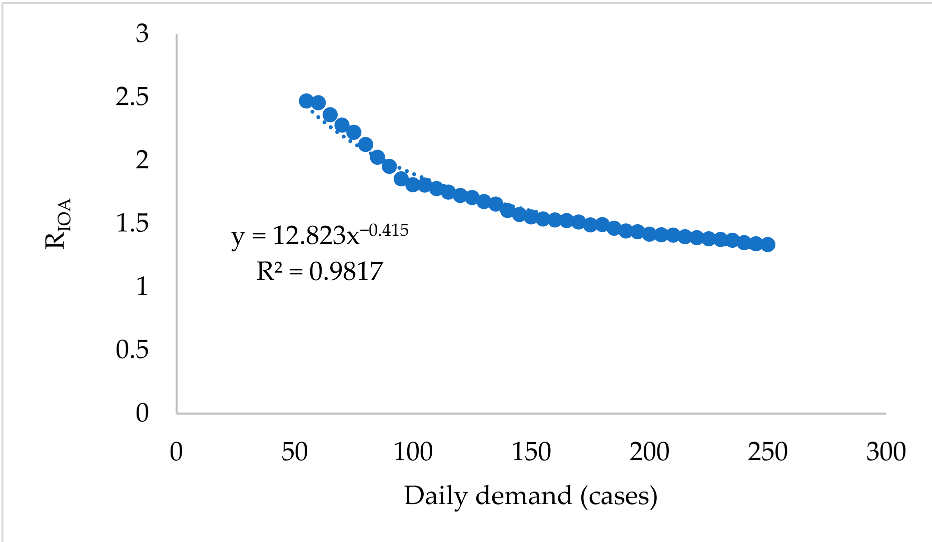

Figure 3. Ratio between output and input pallets of A items for WH1 (scenario 2).

The WH1 throughput for scenario 2 can be written as follows

$$Th1_2 = D_A + D_A\ R_{IOA} + 2N_B\ (1 + PPI_B - 1/N_L) + 2N_C\ PPI_C\ PL_c/L_s + N_C\ PPI_C \quad (23)$$

Equation (20) can be rewritten to be

$$\begin{aligned} Th1 = (D_A + N_A[2\ &+PPI_A])X_{A1} + (D_B + 2N_B + N_B PPI_B)X_{B1} \\ &+(D_C + 2N_C + N_C PPI_C)X_{C1} + (D_A + D_A R_{IOA})X_{A2} \\ &+(2N_B(1 + PPI_B - \tfrac{1}{N_L}))X_{B2} + (\tfrac{2N_C PPI_C PL_c}{L_s} + N_C PPI_C)X_{C2} \\ &+2D_A X_{A3} + 2D_B X_{B3} + 2D_C X_{C3} \end{aligned} \quad (24)$$

4.3. Scenario 2: Simulation for WH2 Capacity of C Items

For A and B items which are usually greater than the layer size, the needed capacity for each item is as the daily demand. For C items, the calculation method is similar to that of scenario 3, as will be explained later. The formula used is:

$$\frac{Cap2_{C2}}{PPI_C} = PL_c N_C \left(\frac{PPI_C}{L_s/PL_c}\right)^{-0.717} \quad (25)$$

where $Cap2_{c2}$ is the needed capacity for the C items if scenario 2 is used. The pallet size (PL_C) is used in the formula to determine the capacity in cases instead of pallets. For example, if the layer size is $L_s = 5$ and the average daily demand is $PPI_C = 1.429$ cases per item, then the ratio between the average daily demand to the layer size is 0.29. The needed capacity for one item is 3.51 (which is 2.45 × 1.429). To check the accuracy of the above equation, simulation was used and it was found that the needed capacity is 3.2. The two numbers are not identical but the formula can be used as a reasonable approximation. If simulation result is utilized, 700 different items will need approximately 2240 storage locations on WH2. However, the number of 700 different items is only for the current day. There are, however, other items active in other days. If the total number of C items are three times the daily active ones, then the total needed capacity will be 6720 storage locations. So the equation will be

$$Cap2_{C2} = TN_C PL_c PPI_C \left(\frac{PPI_C PL_c}{L_s}\right)^{-0.717} \quad (26)$$

The results, if the formula above is used, is somewhat higher than the simulation result. Table 5 (the second part) shows the calculations of WH1 throughput and WH2 capacity for scenario 2. Compared to the second part, the first part has lower total WH1 throughput but higher WH2 capacity.

4.4. Scenario 3: Simulation for WH2 Capacity for B and C Items

In scenario 3, where only full pallets are moving, the WH1 throughput is equal to the daily demand in pallets multiplied by 2. For the WH2 capacity of A items, it is simply the daily demand. For B items, simulation is needed. Table 6 shows the needed capacity of the mini-load system when the daily demand is exactly 20 cases, if complete pallets are depalletized and stored in the mini-load system. The capacity is represented by the number of storage locations of cases. It is assumed that the batch will come just in time when number of cases of a certain item is zero. It is better, however, to keep some safety size. Table 6 shows that the average needed space is 38. Because it is assumed that different items have different cycles, the average is used rather than the maximum value. In other words, the batch of cases arrives on different days for different items, and therefore the maximum, which is the batch size (lot size), is not taken simultaneously for all the items.

Table 6. Needed capacity in WH2 for an item with a daily demand of 20 cases (B items).

Day	Number of Cases at the Beginning of Day (1)	Batch Size (2)	Needed Capacity (Max (1, 2))	Number of Cases at the End of Day
1	50	0	50	30
2	30	0	30	10
3	10	50	50	40
4	40	0	40	20
5	20	0	20	0
Average			38	20

To generalize the results, Table 7 shows the average needed capacity using simulation for different daily demand levels.

Table 7 shows that for a demand level of 10 cases, the needed capacity is 30 cases. For 200 different items, a capacity of 6000 cases is needed. Figure 4 shows the relationship between the ratio of average daily demand per item to pallet size and the ratio of needed capacity to the daily demand per item. Figure 4 is useful to find the capacity of WH2 for scenario 2 (for C items) and scenario 3 (for B items) for a wide range of PPI. The approximation Formulas (26) and (27) are based on the simulation results. In other words, there is no need to make simulation whenever new PPI values occur.

Table 7. Needed capacity of WH2 for B items with different daily demand levels.

Average Daily Demand Per Item	Average Needed Capacity in WH2
5	27.5
10	30
15	36
20	38
25	37.5
30	44
35	47
40	48
45	49.5
50	50

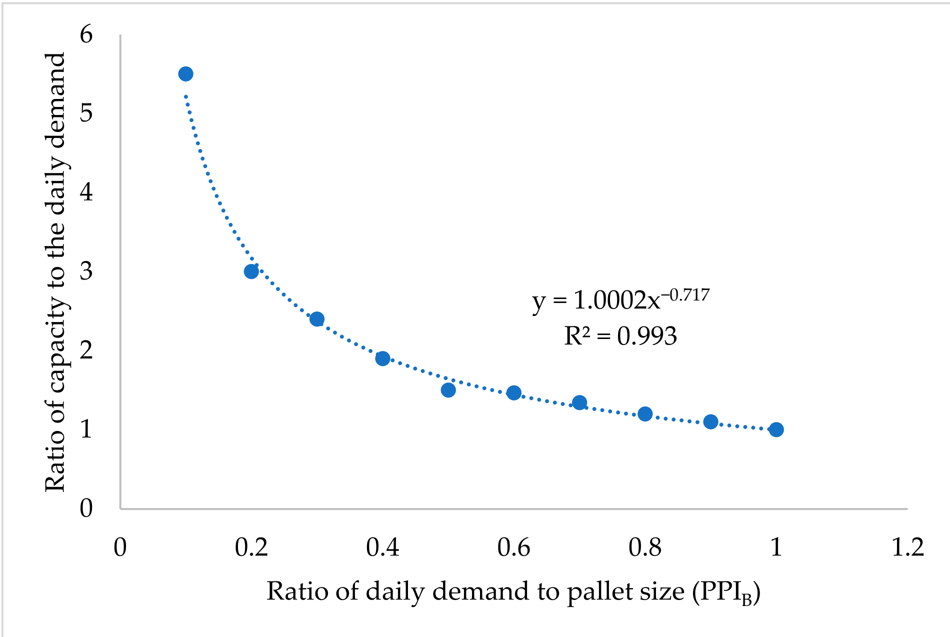

Figure 4. A way to find the needed capacity of WH2 for B items (for scenario 3).

Figure 4 shows that when the daily demand is relatively large (close to the pallet size), lot sizes of layers or pallets will not massively increase the needed capacity if there are a lot of different items in the mini-load system. The capacity needed for B items in scenario 3 is found as follows

$$Cap2_{B3} = N_B PPI_B PL_c \left(PPI_B\right)^{-0.717} \quad (27)$$

For C items, the needed capacity was found using simulation to be 26.0 (for a daily demand of 1.429 cases per item). The needed WH2 capacity for C items is the only simulation result, for WH1 throughput or WH2 capacity that was obtained in this study without providing a wide range of inputs. Therefore, whenever, there is a change in the input parameters, a new simulation result is needed. Based on that, for 700 items, the needed capacity is 18200. When the total number of C items is three times the daily active ones, then a total capacity of 54,600 is needed for the C items on WH2.

Equation (21) can be rewritten to be as follows

$$\begin{aligned} Cap2 = {} & d_A X_{A1} + d_B X_{B1} + d_C X_{C1} + d_A X_{A2} + d_B X_{B2} + TN_C PL_c PPI_C \left(\frac{PPI_C PL_c}{L_s}\right)^{-0.717} X_{C2} + d_A X_{A3} \\ & + N_B PPI_B PL_c \left(PPI_B\right)^{-0.717} X_{B3} + \mathrm{Cap2}_{C3}\, X_{C3} \end{aligned} \quad (28)$$

The last term ($Cap2_{C3}$) is found using simulation. Table 5 (the third part) summarizes the calculations needed for WH1 throughput and WH2 needed capacity

4.5. Results of the Three Scenarios and the Optimal Solution

Figures 5 and 6 give more indication about the results. As expected, the third scenario has the least throughput, while the first scenario has the needed capacity of WH2. Scenario 1 needs so much double handling of pallets in WH1, while scenario 3 requires extra capacity for WH2, especially for C items. Actually C items need careful management for both doubling handling and capacity requirement. This is in spite of the fact that these items are the least important ones. Therefore, it is expected that C items should follow scenario 2 rules to avoid any extra need for throughput or capacity. However, Figures 5 and 6 cannot be enough to determine the best scenario for each class of items. To find the best scenario, it is better to investigate the throughput and the capacity as part of the total costs model. Table 8 shows the full calculations of the total costs with 27 alternatives, where different combinations of lot sizing scenarios for different item classes are considered. They are sorted from the minimum costs to the maximum costs. The throughput in Table 8 is divided by 8 to obtain the throughput per hour.

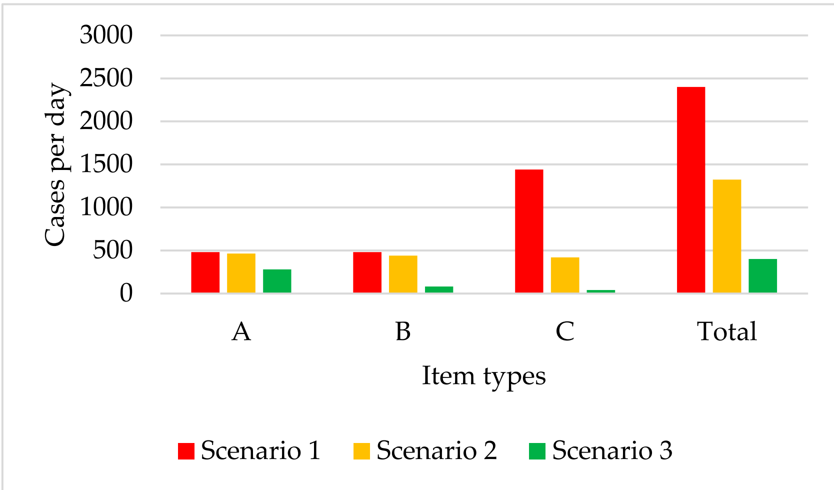

Figure 5. Daily throughput levels for Warehouse 1 for the three scenarios.

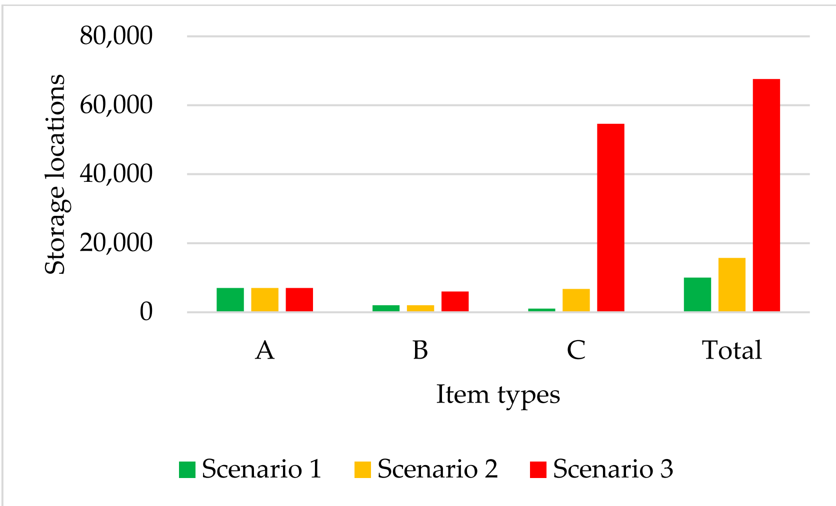

Figure 6. Needed capacity (in cases' storage locations) for Warehouse 2 for the three scenarios.

Table 8. All possible scenarios of A, B, and C items.

#	Scenarios for			WH1 Throughput (Pallets/hour)	WH1 Number of Stacker Cranes	WH 1 Capacity (Pallets)	WH 2 Capacity (Cases)	Total Cost (USD MM)	% Stacker Cranes Costs
	A Items	B Items	C Items						
1	3	3	2	97.5	2	4938	19,720	6.24	78.7
2	3	1	2	147.5	3	5118	15,720	6.59	81.2
3	3	2	2	142.5	3	5118	15,720	6.59	81.2
4	2	3	2	120.4	3	5024	19,720	6.69	79.9
5	1	3	2	122.5	3	5024	19,720	6.69	79.9
6	3	3	3	50.0	1	2974	67,600	6.95	64.4
7	2	2	2	165.4	4	5204	15,720	7.03	82.2
8	2	1	2	170.4	4	5204	15,720	7.03	82.2
9	1	2	2	167.5	4	5204	15,720	7.03	82.2
10	1	1	2	172.5	4	5204	15,720	7.03	82.2
11	3	2	3	95.0	2	3154	63,600	7.29	67.4
12	3	1	3	100.0	2	3154	63,600	7.29	67.4
13	3	3	1	225.0	5	5074	14,000	7.40	84.0
14	2	3	3	72.9	2	3060	67,600	7.40	66.4
15	1	3	3	75.0	2	3060	67,600	7.40	66.4
16	2	3	1	247.9	5	5160	14,000	7.41	83.9
17	1	3	1	250.0	5	5160	14,000	7.41	83.9
18	3	2	1	270.0	6	5254	10,000	7.74	85.9
19	3	1	1	275.0	6	5254	10,000	7.74	85.9
20	2	2	3	117.9	3	3240	63,600	7.74	69.1
21	2	1	3	122.9	3	3240	63,600	7.74	69.1
22	1	2	3	120.0	3	3240	63,600	7.74	69.1
23	1	1	3	125.0	3	3240	63,600	7.74	69.1
24	2	2	1	292.9	6	5340	10,000	7.75	85.8
25	2	1	1	297.9	6	5340	10,000	7.75	85.8
26	1	2	1	295.0	6	5340	10,000	7.75	85.8
27	1	1	1	300.0	6	5340	10,000	7.75	85.8

The number of stacker cranes for the mini-load system (Y_2 = 13) is always the same because the throughput is always the daily demand (10,000 in and 10,000 out of WH2 = 20,000). The throughput per hour for the mini-load system is 2500. The costs found depend on the cost parameters found in Table 1. The total costs include the investment and maintenance costs of stacker cranes and space costs in two warehouses. For example, to calculate the needed WH2 capacity for the first best solution, Equation (28) is used. To determine the variables of this equation, the needed capacity for A items is just the daily demand, the needed capacity for B items is estimated based on Equation (27) which was found based on Figure 4, after extensive simulation. The needed capacity for C items according to scenario 2 is estimated based on Equation (25).

Table 8 shows clearly the tradeoff between the needed number of stacker cranes because of the WH1 double handling and the WH2 needed capacity. For example, solution number 6 contains the lowest number of stacker cranes (only one) where it has zero double handling, but it also contains the maximum needed capacity of WH2 (67,600 cases, which is 7 times the lowest needed capacity found in the last four solutions). However, the effect on the capacity of WH1 is not as large as the effect on the capacity of WH2. The difference between the maximum (5340 pallets) and the minimum capacities (2974 pallets) of WH1 is less than the double. Scenario 3 will lead to a lower number of pallets in WH1 but they are full. In the other two scenarios, some pallets are not full in WH1. As obvious in Table 8, some different solutions can give the same total costs. The best solution is third scenario for A items and B items and the second scenario for C items. It is worth mentioning that the second scenario is the best one for C items for nine of the first ten best options. In others words, for large- and medium-demand items, only full pallets should be moved. For very low demand items, full layers should be depalletized and moved. For example, the first option, a throughput of 780 pallets per day occurs. Only a few options have lower throughput. The optimal solution has a cost of USD 6.24 MM. The difference between the best and the worst scenario is approximately USD 1.51 MM which is an approximately 19.5% cost reduction. Another advantage for the best option here is that it has more capacity of WH2, and therefore it is more capable of responding to any dynamic customer demand, and therefore reducing the lead time. However, the first option with the lowest total cost can be sometimes not feasible if total space of WH1 must be less than 4938 storage locations. In this case, other options can be chosen. One advantage for any option is the sensitivity of the solution. The WH1 throughput in the first solution is 97.5 pallets/hour. If the input data are changed, and the throughput is more than 100 pallets/hour, then more than two stacker cranes are needed in WH1 because the capacity of one stacker crane is 50 pallets/hour. The decision maker should consider that the throughput can be increased in the future, and therefore he/she can use three stacker cranes instead of two, from the beginning. The third scenario of lot sizing is the lowest sensitive one for any increase in demand, while the first scenario is the most sensitive one. Therefore, if any solution contains this first scenario, there should be some enough buffer of capacity. One direction to find the best solution is to reduce the WH1 throughput because this reduction will decrease the needed energy. For the given data, option number 6 is the best regarding this objective. However, this option is very sensitive because there is no capacity buffer. In addition, it is more expensive than the first option. The decision maker might be interested to know the contribution of stacker cranes for the total costs. This contribution according to Table 8 can be from 66.4% to 85.8% of the total costs. The best solution is the one which requires 78.7% of the total costs, which is close to the middle point between the minimum and the maximum values. Moreover, the range of the number of stacker cranes is from one to six, and the best number of stacker cranes was two. This reveals the fact that it is not always true that the minimum number of stacker cranes is the best option, as might be suggested by some authors [24,25]. Increasing the number of stacker cranes has the advantage of absorbing the effect of any increase on the needed throughput. The high contribution of stacker cranes of the total costs is known in the literature [16].

The results of this study are important for the decision makers to determine a fast and yet accurate method for developing a conceptual design of the distribution centers. The proposed decision support system that depends on MS Excel provides an easy and fast method to determine the design that takes into consideration the different configurations of the system and reduces the total costs of the system. The design problem is a strategic one, and once the design is implemented, it is very difficult to make changes on it. Therefore, decision makers must do it right from the first time. The tradeoff between the capacity and throughput that is performed for the first time in this study is expected to provide more accurate results about the needed number of stacker cranes and capacity. However, Table 8 shows only 27 different options. However, more options can be obtained if the lot size considers a flexible coverage period of demand. For example, if the daily demand for a certain item is 12 cases, the following scenarios can be investigated for lot sizes (12, 15, 20, 25, 30, 35, 40, 45, and 50). In the current study, it is assumed that the optimal lot size can be one of the following (12, 15, and 50). These three numbers are related to the three different scenarios. Such a limitation can be studied in future research. Among the advantages of this study is that it considered the reverse movement of pallets, which was mentioned in the literature but not in the context of warehouse design. Therefore, it is difficult to compare the results of this study with the results of previous studies that depend on totally different assumptions and optimization possibilities.

5. Conclusions

In this paper, an efficient approach of lot sizing rules of different product classes that affect the conceptual design of automated distribution center is investigated. Design is defined by the number of stacker cranes, found based on the needed throughput, and the total needed capacity of the two automated warehouses for pallets and cases. The tradeoff between the WH1 throughput and WH2 capacity was investigated. The increase in the throughput of WH1 is due to the double handling of pallets when whole pallets are not depalletized at the same time, as in scenarios 1 and 2. The throughput of the first warehouse and the capacity of the two warehouses depend on the lot sizing rules used. It was found that different rules should be used for different classes of items. Generally, results shows that it is better to move full layers of C items, and full pallets of A and B items. The throughput of the second warehouse depends on the daily demand, and therefore it is fixed. This study is the first to investigate the tradeoff between the throughput and capacity in the two warehouses. The tradeoff is not only for costs. Actually, sustainability tradeoff occurs. One green practice in this study is reducing the space of the second warehouse, and therefore the land area needed. Another green practice is reducing the throughput of the first warehouse, and therefore reducing the needed energy. The best lot sizing rule for each different class of items was found based on a nonlinear integer programming model. Results showed that best solution found can provide savings of up to 19.5% of the total costs. In the best option, the expenses of stacker cranes accounted for approximately 78.7% of the total costs. The decision support tool, which provides the decision maker with a quick technique for warehouse conceptual design, is among this study's primary outputs. Different solutions can provide different methods for green implementation such as reducing the space and energy consumption. Sometimes, it is better not to consider the best theoretical solution because it has more sensitivity to any increase in the demand in the future. This study opens the door for future research, but it does have some limitations. Among the limitations in this study is providing the results of simulation for WH1 capacity requirements instead of formulas that can be used for different parameters. These formulas can be helpful in future research. Moreover, the methodology in this paper did not consider depalletizing more than the average demand except for moving a full pallet or a full layer. Depalletizing one or more pallets or layers was not considered. Future research can investigate this situation. More about the dynamic behavior of the system and the effect of that on the lead time should be considered in future research. Future research can also consider finding the optimal size of safety stock. The assumption of one case in each storage location in the second warehouse is limiting the results of this study. Future research can also investigate different configurations such as assuming that there are two cases in each storage location.

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