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AGGLOMERATIVE AISLE CLUSTERING APPROACH WITH MULTIPLE DEPOTS TO SOLVE ORDER BATCHING, DEPOT ASSIGNMENT, AND ROUTING PROBLEM

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Keywords

Warehouse management, Order batching, Depot assignment, Multiple depots, Multiple order pickers

Abstract

In this study, a heuristic algorithm named "Agglomerative Aisle Clustering (AAC)" is proposed to solve the order batching, depot assignment, and routing problem in a single-block warehouse with 8 aisles, where multiple depots are present, two order pickers are employed at each depot and orders are picked manually. The performance of the proposed algorithm is analyzed from two different perspectives. Firstly, to analyze the effect of the proposed heuristic algorithm on the order batching process, it is compared with the method in which the same warehouse layout properties are used but the order batches are constructed according to the First-Come-First-Served (FCFS) strategy. Secondly, to analyze the integrated effect of both the presence of multiple depots and the proposed heuristic algorithm, it is compared with the method that constructs the order batches according to the FCFS strategy by using warehouse layout that contains a single block with 8 aisles but with single left-most located. Moreover, the third group of analyses are conducted based on two different warehouse layouts which contain multiple depots to emphasize the importance of selected depot positions. For these analyses, customer order databases containing 40 and 60 different

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customer orders are randomly generated, and 40 experiments are conducted for each group. The results demonstrate that the proposed algorithm, aimed at minimizing the total order picking distance, performs 18% better on average across the two order groups when compared to FCFS strategy.

ÇOK DEPOLU MANUEL DEPOLARDA SİPARİŞ GRUPLAMA, DEPO ATAMA VE ROTALAMA PROBLEMİNİ ÇÖZMEK İÇİN AGLOMERATİF KORİDOR KÜMELEME YAKLAŞIMI

Anahtar Kelimeler

Depo yönetimi, Sipariş gruplama, Depo atama, Çoklu depo, Çoklu sipariş toplayıcı

Öz

Bu çalışmada, birden fazla deponun (Giriş/Çıkış noktası) bulunduğu, her depoda iki sipariş toplayıcı çalışanın görev aldığı ve siparişlerin manuel olarak toplandığı 8 koridorlu tek bloklu bir depoda sipariş gruplama, depo atama ve rotalama problemini çözmek için "Aglomeratif Koridor Kümeleme (AKK)" adlı sezgisel bir algoritma önerilmiştir. Önerilen algoritmanın performansı iki farklı açıdan analiz edilmiştir. İlk olarak, önerilen sezgisel algoritmanın sipariş gruplama sürecine etkisini analiz etmek için, aynı depo yerleşim özelliklerinin kullanıldığı ancak sipariş gruplarının İlk Gelen İlk Hizmet Alır (İGİH) stratejisine göre oluşturulduğu yöntemle karşılaştırılmıştır. İkinci olarak, hem birden fazla deponun varlığının hem de önerilen sezgisel algoritmanın bütünleşik etkisini analiz etmek için, 8 koridorlu tek bloklu bir depoda sipariş gruplarını İGİH stratejisine göre oluşturan ancak en solda bir depo bulunan yöntemle karşılaştırılmıştır. Ayrıca, seçilen depo yerlerinin önemini vurgulamak amacıyla, çoklu depo içeren iki farklı depo yerleşimi baz alınarak üçüncü grup analizler yapılmıştır. Analizler için 40 ve 60 farklı müşteri siparişi içeren müşteri sipariş veri tabanları rastgele oluşturulmuş ve her bir grup için 40 deneme gerçekleştirilmiştir. Sonuçlar, toplam sipariş toplama mesafesini en aza indirmeyi amaçlayan önerilen algoritmanın İGİH stratejisi ile karşılaştırıldığında iki sipariş grubunda ortalama %18 daha iyi performans gösterdiğini ortaya koymaktadır.

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1. Introduction

In recent years, people's shopping habits worldwide have evolved in a new direction. Today, almost anything a person might need can be ordered online and delivered to any address in a short time. To meet customer demands in a timely and effective manner, warehouse operations has become crucial for all companies.

De Koster, Le-Duc, and Roodbergen (2007) stated that warehouse activities can include 6 main operations which can be listed as receiving, transfer and put away, order picking/selection, accumulation/sortation, cross docking and shipping. These operations can be explained briefly as follows:

- In *receiving* operation, coming items that arrive to the warehouse are unloaded from the truck or transporter vehicle and updating the stock data according to the information of coming items.
- In *transfer and put away* operation, unloaded items from the truck are carried and placed to the shelves or storage locations. In some situation, repackaging process can be needed such as separating pallets into smaller bins or packages.
- In *order picking/selection* operation, the requested items from customers are gathered from storage locations. In the literature, it is stated that order picking operation is one of the costliest and labour-intensive operations in warehouse activities. Also, it should be stated that, the performance of order picking operation is affected from other followed strategies such as storage assignment, routing, scheduling etc.
- In the *accumulation/sortation* process, collected items of one customer order are bunched together and rearranged to send the customer. This process is needed if one customer order is splitted to more than one batch and picked from shelves in different order picking tours.
- The *cross-docking* operation is needed when the coming items will be directly transferred to the shipping docks.
- In the *shipping* process, items are dispatched to the customers or distribution centres (DCs).

Due to including high cost and labour sensitivity, order picking operations are excessively studied by researchers from various perspectives. Pinto, Nagano, and Boz (2023) stated that order picking systems can be classified two main categories. While the first one is the automation strategies and processes, the second group is picking optimization policies. Although the scope and complexity of warehouse operations vary according to the technological infrastructure and equipment of the firms, number of human workforce and preferred management strategies, it is possible to mention 3 main warehouse processes which are *order batching, storage assignment,* and *routing*. Moreover, the applied strategy in one of these operations can impact other processes or emerge some new problems or operations that should be handled. For example, applying pick-and-sort order picking strategy requires an additional process which are called sorting. Therefore, understanding the scope and purpose of each warehouse operation and implementing the right management strategies are critical to increase warehouse overall efficiency.

In the context of order picking process, this study handles order batching, depot selection and assignment problem with multiple depots and multiple pickers. To solve mentioned problem a new constructive heuristic algorithm called as ***"Agglomerative Aisle Clustering (AAC)"*** is proposed and 320 experiments are conducted on the order groups that contain 40 and 60 customer orders. In the literature, most of the studies handle order picking problems considering warehouse layout with single left-most located depot. On the other hand, this study considers multiple depots and multiple pickers simultaneously and therefore, much more suitable to meet the real-world business dynamicity. Also, the proposed AAC algorithm does not include any important tuning parameter as in other algorithms such as GA, TS, etc. In other words, the AAC algorithm is straight-forward, problem-specific and easily applicable to small and medium sized manually operated warehouses. This study is expected to contribute to the literature by proposing new solution approach and handling the warehouse layout as variable zoning strategy. The expected contribution is also explained in detail in Section 3.

The remainder of this study is organized as follows: Section 3 provides the explanation of proposed heuristic algorithm with an illustrative example. Section 4 presents the results of the experimental analysis with a critical perspective. Finally, Section 5 presents the conclusion section and summarizes the study.

2. Literature Review About Order Picking

As stated earlier, order batching, storage assignment, and routing are 3 main operations that have significant impact on the performance of order picking process. One of the most studied operations by researchers is order batching and this process has significant impact on warehouse efficiency. ***Order batching*** means the determination of which customer orders can be collected in one order picking tour to minimize total order picking distance like in the study of Hsu, Chen and Chen (2005) and Wang, Wang, and Mi (2017) and/or total picking time in the study of Gil-Borrás, Pardo, Alonso-Ayuso, and Duarte (2021). In the literature, different solution approaches are proposed by researchers to handle order batching problem. Exact solution approaches such as Mixed-Integer Linear Programming (MILP) are employed to optimally solve order batching problem (Aboelfotoh, 2019; Öncan, 2015; Tran-Vo, Nguyen, and Hong, 2022). On the other hand, Gademann and Velde (2005) proved that the order batching problem belongs to the NP-Hard problem class and if there are no more than two customer orders in a batch, the order batching problem can be solved in polynomial time. But constructing a batch with only two customer orders is not realistic at all. Therefore, researchers preferred to develop heuristic/metaheuristic algorithms such as Iterated Descent Algorithm by Gademann and Velde (2005), Iterated Local Search (ILS) by Henn (2012), Classic Tabu Search (Classic TS) and Attribute- Based Hill Climber (ABHC), by Henn and Wäscher (2012), Genetic Algorithm (GA) by Hsu et al. (2005) to find near optimal solutions in reasonable time. Regarding customer order availability, Henn (2012) explained two types of order batching methods which are called static (off-line) order batching and dynamic (online) order batching. If all of customer orders are available at the beginning of the batching process and there is no change during batching, this method is called ***static order batching.*** However, in ***dynamic order batching***, coming customer orders to the system is a continuum process and the availability of customer orders dynamically change over time. As expected, solving the online order batching problem is much more difficult than solving the static order batching problem, but it is closer to real-life dynamic business conditions. Online order batching problem has been handled in recent years by researchers with solution approaches such as Column Generation proposed by van der Gaast, Jargalsaikhan, and Roodbergen (2018), ILS developed by Alipour, Mehrjedrdi, and Mostafaeipour (2020), Ant Colony Algorithm (ACO) and Artificial Bee Colony Algorithm proposed by Hojaghani, Nematian, Shojaie, and Javadi (2021), as it better represents the real world business conditions.

The second primary warehouse management process is ***storage assignment.*** This process can be defined as the strategy that determines assignment of stock keeping units (SKUs) to storage shelves in warehouses (Kübler, Glock, and Bauernhansl, 2020). De Koster et al. (2007), explained five frequently applied storage assignment policies with different advantages and disadvantages. These strategies can be listed as random storage, dedicated storage, full turnover storage, closets open location storage and class-based storage. In literature, storage assignment problem is handled with different solution approaches. For instance, Petersen, Aase, and Heiser (2004) used simulation approach to analyze the effect of number of storage classes, partition of items to classes and performance of applied storage assignment strategy. On the other hand, Yu, de Koster, and Guo (2015) developed an algorithm to determine optimal number and boundaries of storage classes and at the end of the study it is found that generally small number of classes yield optimal result. Otherwise, Guo, Yu, and de Koster (2016) determined the size of the required storage space (RSS) which varies according to item demand and item-space sharing along with analyzing its impact on performance of applied storage assignment strategy in a warehouse. In addition to this, Elevli and Dinler (2023) applied PROMETHEE method, which is one of the multi-criteria decisions making (MCDM) methods used for pairwise comparisons, to determine the storage locations of all products by the company. At the end of the applied method, not only is the usage rate of storage area increased but also transportation distances are minimized. Essentially, researchers preferred to handle storage assignment problem with combination of other warehouse management processes like integration of storage and batching (Hsieh and Tsai, 2006), or combination of storage assignment, batching and routing (Chackelson, Errasti, Ciprés, and Lahoz 2013; Ene and Öztürk, 2012; Hsieh and Huang, 2011; Petersen and Aase, 2004). In contrast to these most basic storage assignment strategies, mixed-shelves storage strategy is developed. This strategy is more suited to the way of work of e-commerce retailers (i.e., processing hundreds of customer orders which consist of several order lines with small order quantities in a tight time window). In mixed-shelves storage strategy, the same SKU is placed in different storage shelves over the warehouse. In other words, the items of one SKU can be picked from more than one divergent location in the warehouse. In one of the studies about mixed-shelves storage; Weidinger, Boysen, and Schneider (2019) proposed an improvement heuristic to handle picker routing problem in a warehouse where mixed-shelves storage strategy is applied. On the other hand, Xie, Li and Luttmann (2023) preferred to combine mixed-shelves storage with automated guided vehicles (AGVs) to solve integrated order batching and routing problems employing a novel Variable Neighborhood Search (VNS) algorithm.

The final essential warehouse operation mentioned above is ***routing.*** This operation can be defined as determining the order in which the SKUs on the picking list are retrieved from the storage shelves by order pickers, with the aim of minimizing the total order picking distance. In practice, heuristic approaches are often preferred over finding the optimal route for several reasons. First, it is not always feasible to determine an optimal route for every warehouse layout. Second, optimal routes may not always be intuitive for the order picker, leading to modifications that could result in a greater distance than the original optimal route. Due to these two primary reasons, five heuristic routing methods—S-shape, largest gap, return, midpoint, and combined—are commonly applied in real-world business applications. Furthermore, researchers have addressed the routing problem from various perspectives in literature. At the beginning of the 2000s, Roodbergen and de Koster (2001), used Dynamic Programming and simulation approaches to solve routing problem. In this study, they compared the average travel time for two warehouse layout types, which contain and not contain middle aisles. The results of the simulation experiments showed that the presence of middle aisle in warehouses results in shorter average travel time. On the other hand, Theys, Bräysy, Dullaert, and Raa (2010), preferred to use Lin-Kernighan-Helsgaun (LKH) heuristic, one of the known Travelling Salesman Problem (TSP) heuristic, to solve routing problem. At the end of the study, it is found that LKH heuristic outperforms well-known routing heuristics. In another study, Bottani, Casella, and Murino (2021), developed a hybrid metaheuristic algorithm that combines Harmony Search (HS) with the Floyd-Warshall (FW) to handle routing problem and performance of the proposed algorithm is compared with the results of Water Wave Optimization (WWO), S-shape and largest gap heuristics. On the other hand, in one of the recent articles, Saylam, Çelik, and Süral (2024) proposed arc routing-based binary integer programming model to solve routing problem in both one block and two-block warehouse layouts. The results showed that the developed model can solve large-size problems in a short time when compared to other methods present in the literature.

With the changing situations and conditions in the way of working of firms, some new problems that should be considered emerge over time. For instance, in earlier studies, authors assumed that single order picker is employed in warehouses but this assumption is not realistic at all. Over time, employing multiple pickers is taken into consideration and this time the assignment of constructed batches and/or customer orders to pickers arises as a new problem that needs to be solved. This problem is called as ***assignment problem*** in the literature (Ardjmand, Shakeri, Singh, and Sanei Bajgiran, 2018). In addition to this, when the sorting of assigned orders or batches for each picker is considered, then the problem becomes a scheduling problem. While in some studies, the combination of assignment and sequencing problems is called as ***scheduling*** (Haouassi, Kergosien, Mendoza, and Rousseau, 2022; van Gils, Caris, Ramaekers, and Braekers, 2019); in another studies it is seen that these problems are written as separately (Cano, Cortés, Campo, and Correa-Espinal, 2021; Scholz, Schubert, and Wäscher, 2017).

In addition to the emergence of new challenges that need to be addressed, tackling the integrated management of warehouse processes marks another significant milestone in the warehouse management literature. Over time, researchers realized that handling mentioned problems separately generates sub-optimal results and therefore, addressing warehouse management processes in a holistic manner can have a potential to produce much more effective results (Scholz et al. 2017). To solve the integrated form of these problems, different solution approaches are proposed. For example, to solve combined form of order batching and picker routing problem Cheng, Chen, Chen, and Jung-Woon Yoo (2015) proposed hybrid approach of Particle Swarm Optimization (PSO) and Ant Colony optimization (ACO); Valle, Beasley, and Cunha (2017) improved Integer Programming (IP) with valid inequalities. Kulak, Şahin, and Taner (2012) suggested Cluster-based TS Algorithm and Lin, Kang, Hou, and Cheng (2016) developed Improved PSO algorithm. Additionally, for the case of multiple pickers, there are also studies that solve order batching, routing, and picker scheduling problems in an integrated manner. In one of these studies, Scholz et al. (2017) developed a mathematical model to solve small-sized problems and Variable Neighborhood Descent (VND) Algorithm for large-sized problems. On the other hand, van Gils et al. (2019) suggested Iterated Local Search Algorithm to handle mentioned problem. Lastly, in a study published in recent years, Kübler et al. (2020) developed Discrete Evolutionary PSO (DEPSO) to solve joint dynamic storage location assignment, order batching, and picker routing problem.

In the literature, most of the studies focus on the fundamental warehouse operations such as order batching, routing, or assignment problems to find optimal solutions or improve the performance of the current strategy. Few studies handle warehouse operations regarding human factors and ergonomic conditions. In one of these studies, Binici and Yenisey (2023) proposed a capacity-constrained mathematical model to solve order batching and routing problem with the aim of minimizing human energy expenditure in high-level warehouses. In this study, authors used Manhattan distance-based Tchebychev formulas to calculate human energy expenditure and the performance of the proposed method is compared with FCFS batching strategy and S-shape routing heuristic. In another study that considers human factors, Günay (2024) developed two-stage stochastic model with the aim of minimizing assignment and overtime costs. Also, the author prevented excessive fatigue levels by including rest allowance into picking tour. Lastly, Tutam and de Koster (2024) applied dynamic programming approach with the aim of minimizing total order picking time and pickers' knee flexion occurring get on the cobot for warehouse system that employs cobots for collaborative order picking. In this study, authors found that the optimal collaboration strategy has potential to decrease total travel time and pickers' knee flexion.

When the warehouse management literature is search in detail, it is realized that generally one left-most located depot (Input/Output –I/O- point) is used for manually operated warehouses. There are very few studies that address the problems by considering the case of using multiple depots. In one of these studies, Won and Olafsson (2005) handled joint order batching and picker routing problem and developed two heuristic algorithms as solution approaches. On the other hand, Tran-Vo et al. (2022) solved batching problem applying Mixed-Integer Lineer Program (MILP) approach for multiple depot situation with the aim of minimizing total travel distance with ensuring workload balance among depots. Recently, the study published in this year, Gülyeşil and Durmuşoğlu (2024) proposed a new mathematical model for small-sized problems and a new version of Harmony Search (HS) metaheuristic algorithm called Dependent Harmony Search (DHS) for large-sized problem to solve order batching, depot selection, and assignment problem for not only multiple depots situation but also taking into consideration multiple pickers.

Consequently, this study handles order batching, depot assignment and routing problems under multiple depots and multiple pickers considerations by proposing a new constructive heuristic algorithm that is called ***Agglomerative Aisle Clustering (AAC).*** The performance of the proposed algorithm is measured from two perspectives. In the first experiment group, the performance of the AAC algorithm is compared FCFS batching strategy considering warehouse layout with three-depots located at the beginning of aisles 1, 4, and 8. In the second group of experiments combined effect of AAC algorithm and constructing multiple depots is analyzed. To examine this combined effect FCFS order batching strategy is used with considering warehouse layout with single left-most located depot. Lastly, to analyze the impact of depot locations, the performance of the AAC algorithm is measured based on two different warehouse layouts. In the first warehouse layout, two-depots are located at the beginning of aisles 2, and 7; and in the second warehouse layout three-depots are located at the beginning of aisles 1, 4, and 8. It is expected that this study contribute to the warehouse management literature by proposing easily applicable heuristic algorithm, the AAC algorithm, for small and medium sized firms and by conducting experiment from different perspectives.

3. Method

3.1. Agglomerative Aisle Clustering Approach

This study proposes a new heuristic algorithm to solve order batching, depot assignment and routing problem for warehouses which construct multiple depots and employ multiple pickers. In most of the studies, only one left-most located depot is applied (Haouassi et.al., 2022; Henn and Schmid, 2013; Henn, 2015; Shqair, Altarazi, and Al-Shihabi, 2014). On the other hand, the effect of using multiple depots instead of one depot is analyzed in scarce research (Gülyeşil and Durmuşoğlu, 2024; Tran-Vo et al., 2022). As stated before, to solve order batching problem for large size problems, several heuristic and/or metaheuristic algorithms are proposed like Iterated Descent Algorithm (Gademann and Velde, 2005), Classic TS and Attribute Based Hill Climber (ABHC) (Henn and Wäscher, 2012), or exact solution approaches (Aboelfotoh, Singh and Suer, 2019; Muter and Öncan, 2015; Öncan, 2015). This study assumes multiple depots in an 8-aisles warehouse and when multiple depots situation is considered, assignment of customer orders to depots arises as a new problem that should be handled. Also, due to considering multiple pickers, the assignment of customer orders to each order picker arises as a new problem.

The following assumptions are considered in this study:

i. In this study, three different warehouse layouts with 8-aisles one-block storage area are considered. In the first layout, three-depots are located at the beginning of aisles 1,4, and 8. In the second layout, two-depots are constructed at the beginning of aisles 2, and 7. Finally, a warehouse layout with the single left-most located depot is considered. These three warehouse layout types are used in experiments.

ii. One-way S-shape routing strategy is applied. For 8-aisles warehouse, 33 different one-way S-shape routes are available and to solve the routing problem, one of these routes that complies with the constructed batch should be selected.

iii. An order picker should start and end the order picking tour in the same depot.

iv. Two pickers are employed at each depot and the workload balance between them is taken into consideration.

v. The warehouse considered is fully manually operated.

vi. Random storage strategy is applied in this warehouse and one type of item (or stock keeping unit – SKU) can be stored only one location.

vii. While constructing batches, order integrity should be satisfied. This means that, all items in a customer order should be assigned only one batch and collected only one picker.

viii. The selected order picking strategy is a sort-while-pick strategy and batch capacity is determined as 5 different customer orders.

ix. The volume and weight of the items are neglected, and it is assumed that all items are sized to fit into the picking cart.

x. Each customer order can contain a minimum of 1 and a maximum of 3 different SKUs.

xi. Workload balance among multiple depots is out of scope in this study.

Figure 1, Figure 2 and Figure 3 illustrate the warehouse layouts used in the analysis, along with the route directions for one-way S-shape routing. In Figure 1; there are three-depots which are located at the beginning of aisles 1, 4, and 8, while in Figure 2 two-depots are located at the beginning of aisles 2 and 7. Finally, in Figure 3 there is a single depot located at the beginning of aisle 1 on the leftmost side.

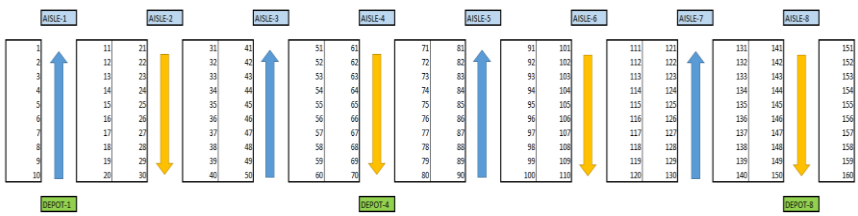

Figure 1. Representation of One-Way S-shape Route Directions and Three-Depots Locations

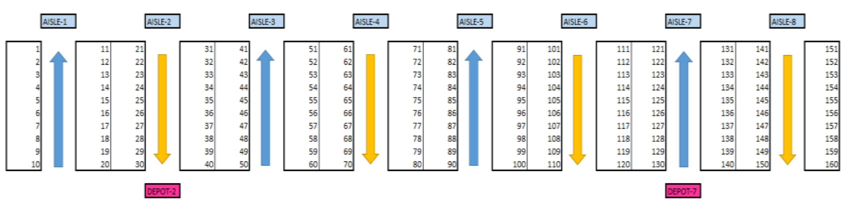

Figure 2. Representation of One-Way S-shape Route Directions and Two-Depots Locations

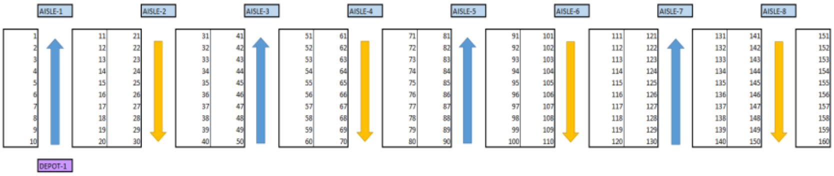

Figure 3. Representation of One-Way S-shape Route Directions and Single Left-Most Depot Location

As can be seen from these figures, 20 different SKUs are stored in each aisle and the width of each aisle is wide enough to pick the products from the shelves on both sides. On the other hand, the lenght of each route is calculated based on the predefined formula that is explained in the study of Gülyeşil and Durmuşoğlu (2024) and detailed information can be found in this study.

The steps of the proposed AAC algorithm for warehouse layout with three-depots can ben explained as follows:

Step 1. In the first step, all customer orders are grouped into three different categories based on the SKU numbers included. If SKU numbers of all items in a customer order smaller than or equal to 40, this order is labelled as “category-1” and assigned to Depot-1. If SKU numbers of all items in a customer order bigger than 120, this order is labelled as “category-2” and assigned to Depot-8. All other customer orders that are not included in category-1 and category-2 are labelled as “skipped orders”.

Step 2. In this step, all skipped orders are grouped in two different categories as in the first step. But the categorization condition differs in the second step. If all SKU numbers in a customer order is smaller than or equal to 80, this order is labelled as “category-3” and assigned to Depot-4. If all SKU numbers in an order is bigger than 80, this order is labelled as “category-4” and assigned to Depot-8. All other orders which not belong to category-3 or category-4 remain with the label “skipped orders”.

Step 3. This step can be considered as AAC phase. At this stage, only skipped orders that are not assigned to any depot are considered. Firstly, the aisles required for picking the products from the shelves in each order are determined. Then, the order with the least number of aisles is selected. After that, the 4 most similar orders according to sharing the most common aisles with the first selected order is found. Afterwards, all necessary aisles to collect these 5 selected orders are determined and the smallest route that covers all required aisles is selected from the 33 different route options. The depot which offers the minimum distance for the determined route is identified and these 5 customer orders are assigned to this depot. These stages are repeated until all skipped orders are assigned to one of the three-depots.

Step 4. At the end of Step 3, all customer orders have been assigned to Depot-1, Depot-4, or Depot-8. At this step, order batching is performed for customer orders assigned to each depot. When constituting order batches, customer orders are included in the same batches based on their similarity. This means that, customer orders which shares most common aisles are included in the same batch and each batch includes 5 different customer orders (i.e., batch capacity is equal to 5).

Step 5. This step is the assignment of constructed batches to order pickers in consideration of workload balance between them. After all batches are constructed for each depot, the routes and distance of these routes are determined. The distances of routes are sorted from largest to smallest and the first route which has the longest distance is assigned to picker 1. The second route is assigned to picker 2 and all remained routes are assigned respectively selecting the picker who has least workload. These proses is repeated until all batches and routes are apportioned between two order pickers.

The proposed heuristic for the warehouse layout with three-depots is explained in detail until so far. Also, the flowchart of the heuristic is shown in Figure 4.

The expected contributions of this study to the literature can be listed as follows:

- The proposed heuristic algorithm contributes to the literature by categorizing orders into groups based on the SKUs they contain and assigning them to depots, accordingly, as outlined in Step 1 and Step 2. This approach applies a variable zoning strategy. One of the articles published in recent years, synchronised dynamic zone picking strategy is integrated with picker routing and workload balancing problem and the authors proposed Dynamic Programming approach to solve this problem (Saylam, Çelik, and Süral, 2023). However, the mentioned study differs from our work with the warehouse layout where only one left-most located depot assumption, determined objective function, and proposed solution approach.
- As second contribution, the batching process in the proposed heuristic can be viewed as a two-phase approach. In the first phase, orders are assigned to depots using the variable zone strategy and the AAC algorithm (Steps 1, 2, and 3) for the warehouse layout with three-depots. In the second phase (Step 4), order batching is conducted based on similarity, and picking lists are prepared by the end of Step 4. This two-phased approach is considered another significant contribution to the existing warehouse management literature. Moreover, by applying Step 5, assignment of batches to multiple pickers are also taken into consideration simultaneously with multiple depots situation.

- As a third contribution, to emphasize the importance of depot position effect on total order picking distance, two different warehouse layouts with multiple depots are used in experiments.
- In the warehouse management literature, algorithms such as TS (Henn and Wäscher, 2012), and Iterative Descent Algorithm (Gademann and Velde, 2005), that produce efficient results for warehouse problems are also proposed. In addition to producing efficient results, these algorithms involve parameter decisions that have significant impact on algorithm performance (Almufti, Shaban, Ali, and Fuente, 2023). For example, in TS algorithm, it is very important to correctly specify parameters such as tabu tenure and neighbourhood structure. On the other hand, the proposed AAC algorithm in this paper is easy to implement as there are no parameters that can affect performance, which can be a great advantage for practitioners.

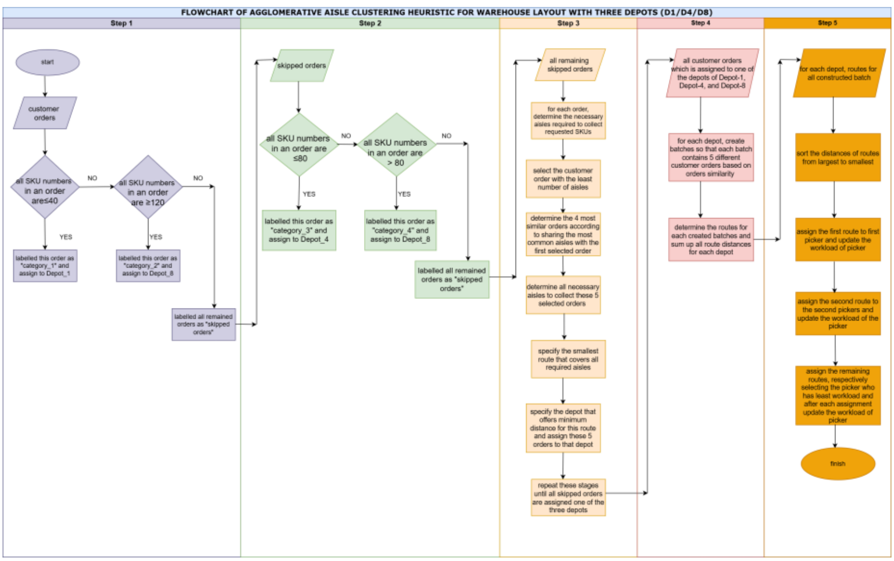

Figure 4. Flowchart of Agglomerative Aisle Clustering (AAC) Heuristic Approach for Warehouse Layout with Three-Depots

In this study, research and publication ethics were followed. Ethics committee approval is not required in this study.

3.2. Illustrative Example for the Proposed Heuristic Algorithm

To better clarify the steps of the proposed algorithm, an example containing 40 customer orders is explained below:

customer_orders = {1: [122], 2: [61], 3: [108], 4: [124, 111], 5: [98, 6], 6: [105], 7: [121, 157, 100], 8: [104], 9: [84, 7, 79], 10: [110], 11: [35], 12: [27, 100], 13: [59, 28, 42], 14: [69, 31], 15: [94], 16: [85], 17: [147, 50, 77], 18: [28, 127], 19: [68], 20: [136], 21: [155, 9], 22: [111], 23: [142], 24: [107, 75, 82], 25: [34, 2, 68], 26: [80, 132, 1], 27: [55, 144], 28: [110, 122, 24], 29: [127, 6], 30: [26, 65, 73], 31: [33, 8], 32: [150, 59], 33: [49], 34: [146], 35: [105], 36: [4, 90], 37: [136], 38: [115], 39: [131, 81], 40: [60, 59]}

In this dataset, the dictionary key represents the order number, while the value, shown as a list, contains the SKU numbers for that order. For example, order-1 includes the SKU number 122, while order-7 includes the SKU numbers 121,157, and 100.

Step 1. At the end of Step 1, customer orders 11 and 31 are labelled as category-1 and customer orders 1, 20, 23, 34, and 37 are labelled as category 2. In this step, the list of orders labelled as skipped orders and assignment of orders 11, 31, 1, 20, 23, 34 and 37 are as follows:

Skipped orders = [2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14, 15, 16, 17, 18, 19, 21, 22, 24, 25, 26, 27, 28, 29, 30, 32, 33, 35, 36, 38, 39, 40]

Depot-1 orders = [11, 32]

Depot-8 orders = [1, 20, 23, 34, 37]

Step 2. At the end of Step 2, customer orders 2, 13, 14, 19, 25, 30, 33, and 40are included in category-3 and assigned to Depot-4. On the other hand, customer orders 3, 4, 6, 7, 8, 10, 15, 16, 22, 35, 38, and 39 are included in category-4 and assigned to Depot-8. These orders are removed from skipped orders list and final assignment of orders to depots and last content of skipped order list will be as follow:

Skipped orders = [5, 9, 12, 17, 18, 21, 24, 26, 27, 28, 29, 32, 36]

Depot-1 orders = [11, 31]

Depot-4 orders = [2, 13, 14, 19, 25, 30, 33, 40]

Depot-8 orders = [1, 20, 23, 34, 37, 3, 4, 6, 7, 8, 10, 15, 16, 22, 35, 38, 39]

Step 3. In this step, the final skipped orders list is considered and required aisles to collect items of each customer order are determined. The following "skipped orders aisles" list show the result:

Skipped orders aisles = {5: [5, 1], 9: [5, 1, 4], 12: [2, 5], 17: [8, 3, 4], 18: [2, 7], 21: [8, 1], 24: [6, 4, 5], 26: [4, 7, 1], 27: [3, 8], 28: [6, 7, 2], 29: [7, 1], 32: [8, 3], 36: [1, 5]}The required aisles for these orders are identified as {1, 2, 3, 4, 6, 7, 8}

Selected Orders: [5, 9, 36, 12, 21]

Required Aisles: {1, 2, 4, 5, 8}

Best Route: 27, Best Depot: 1

After this assignment, the list of skipped orders is updated and the new list of skipped orders is [17, 18, 24, 26, 27, 28, 29, 32].

The process is repeated twice in this example until all skipped orders are batched and assigned one of the depots.

Selected Orders: [18, 28, 26, 29, 17]

Required Aisles: {1, 2, 3, 4, 6, 7, 8}

Best Route: 33, Best Depot: 1

Remaining Skipped Orders: [24, 27, 32]

Selected Orders: [27, 32, 24]

Required Aisles: {3, 4, 5, 6, 8}

Best Route: 32, Best Depot: 4

At the end of Step 3, the final assignment of orders to each depot will be as follows:

Depot 1 Orders: [11, 31, 5, 9, 36, 12, 21, 18, 28, 26, 29, 17]

Depot 4 Orders: [2, 13, 14, 19, 25, 30, 33, 40, 27, 32, 24]

Depot 8 Orders: [1, 20, 23, 34, 37, 3, 4, 6, 7, 8, 10, 15, 16, 22, 35, 38, 39]

Step 4. At the beginning of Step 4, all orders have been assigned to one of the three-depots and at this step all orders in each depot are batched according to their similarity. Based on the constructed batches, necessary routes and distances of these routes are identified.

For the example given above, the final batches, routes and distance of each depot can be shown as follows:

<u>Depot 1 Batches and Routes:</u>

Depot_1 batch_1 = [36, 5, 9, 11, 12]

Depot_1 route of batch_1 = 26, Distance = 156

Depot_1 batch_2 = [17, 18, 21, 26, 28]

Depot_1 route of batch_2 = 33, Distance = 210

Depot_1 batch_3 = [29, 31]

Depot_1 route of batch_3 = 16, Distance = 126

Depot_1 total distance = 492

Depot 4 Batches and Routes:

Depot_4 batch_1 = [32, 40, 13, 33, 2]

Depot_4 route of batch_1 = 27, Distance = 168

Depot_4 batch_2 = [14, 19, 24, 25, 27]

Depot_4 route of batch_2 = 33, Distance = 210

Depot_4 batch_3 = [30]

Depot_4 route of batch_3 = 11, Distance = 102

Depot_4 total distance = 480

Depot 8 Batches and Routes:

Depot_8 batch_1 = [1, 34, 3, 4, 37]

Depot_8 route of batch_1 = 25, Distance = 102

Depot_8 batch_2 = [6, 35, 7, 8, 10]

Depot_8 route of batch_2 = 25, Distance = 102

Depot_8 batch_3 = [15, 16, 20, 22, 23]

Depot_8 route of batch_3 = 25, Distance = 102

Depot_8 batch_4 = [38, 39]

Depot_8 route of batch_4 = 25, Distance = 102

Depot_8 total distance = 408

Total distance for all depots = 1380

Step 5: At this step, constructed batches and routes are partitioned between order pickers in consideration of workload balance. Firstly, the distances of routes are sorted from largest to smallest. The first highest distance and route is assigned to picker 1. The second highest distance and route is assigned to picker 2. All remaining routes are assigned respectively selecting the picker who has least workload. This assignment process is executed in all depots.

Batch-Picker Assignment for Depot 1:

Sorted list of routes and distances: {33: 210, 26: 156, 16:26}

Based on this sorted list, firstly batch 2 (route 33) is assigned to picker 1. The batch 1 is assigned to picker 2. For the last batch (batch 3), the workload of picker 2 is less than picker 1, this batch is assigned to picker 2.

Assigned batches to picker 1 = [2]

Assigned batches to picker 2 = [1, 3]

<u>Batch-Picker Assignment for Depot 4:</u>

Sorted list of routes and distances: {33:120, 27:168, 11:102}

Assigned batches to picker 1 = [2]

Assigned batches to picker 2 = [1,3]

<u>Batch-Picker Assignment for Depot 8:</u>

Sorted list of routes and distances: {25:102, 25:102, 25:102, 25:102}

Assigned batches to picker 1 = [1,3]

Assigned batches to picker 2 = [2,4]

At the end of Step 5, the execution of proposed AAC heuristic algorithm is completed.

To better explain the logic and the steps of the proposed AAC algorithm, an illustrative example is given based on a warehouse layout with three-depots. For the warehouse layout with two-depots, a modification is made to the proposed heuristic algorithm. For the latest warehouse layout, the variable zoning strategy is applied only in the first step. That is, in Step 1, orders with all items less than or equal to 80 are assigned to Depot-2 and orders with all items greater than 80 are assigned to Depot-7. All remaining orders are labeled as “skipped orders” and then AAC heuristic is applied on these skipped orders list. In other words, Step 2 of the algorithm that is explained for the warehouse layout with three-depots is removed in the mentioned modification and the handled problem is solved with four steps in total. The flowchart of the modified AAC algorithm for two-depots warehouse layout is given in Figure 5.

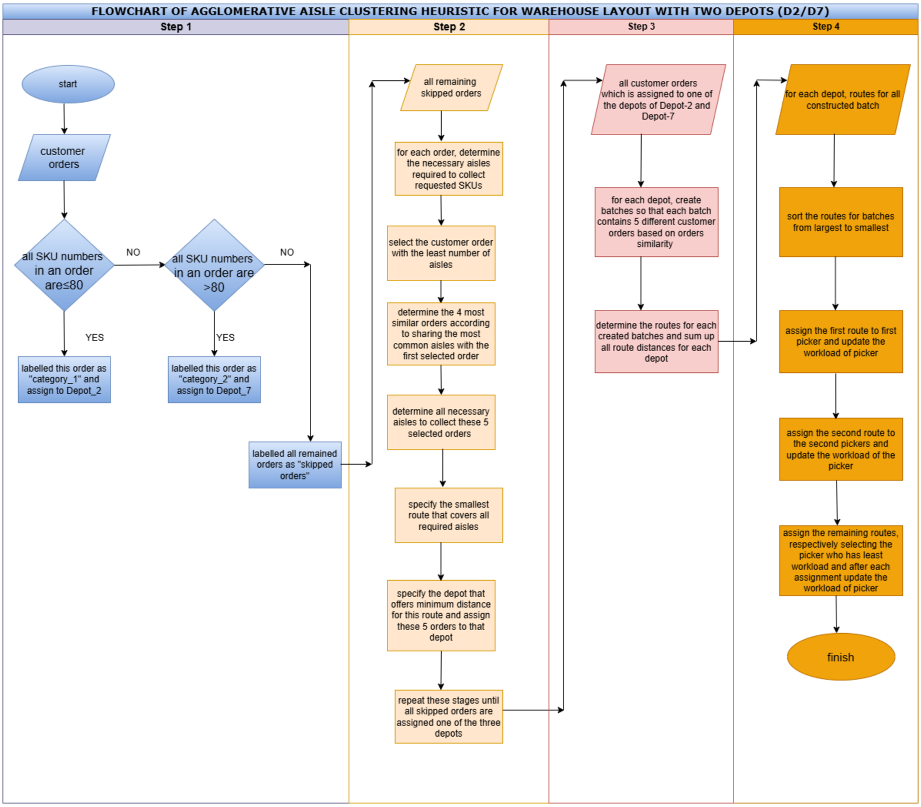

Figure 5. Flowchart of Agglomerative Aisle Clustering (AAC) Heuristic Approach for Warehouse Layout with Three-Depots

The performance of the proposed algorithm is analyzed from two perspectives. Also, selection of depot position affect is analyzed with experiments. The explanation of these analyses and related results are given in the "Results and Discussion" section.

4. Results and Discussion

To analyze the performance of the proposed algorithm, three main analyses are conducted. The purpose of the first group of analysis is to analyze the performance of the proposed algorithm only. In other words, the first analysis investigates the effect of using AAC approach for order batching process against using FCFS strategy. For this purpose, 40 different experiments are conducted for two distinct order categories as 40, and 60 orders. The first 10 results of these analyses are shown in Table 1, and Table 2 for order groups of 40, and 60 orders, respectively. The mean % difference obtained from 40 experiments are found

17.32%, and 19.94% for 40, and 60 orders groups, respectively. As can be seen from these results, while the number of processed customer orders increases, the benefit of using the AAC approach for order batching also increases. Based on this result, it can be said that employing the AAC approach for order batching has a significant impact, especially for e-commerce firms where number of thousands of customer orders are processed daily.

Table 1
First 10 Result Experiments of Comparison Between AAC Method Against FCFS Batching Strategy in Three-Depots Warehouses for 40 Orders

Experiment number	AAC with three-depots	FCFS with three-depots	% difference
Exp_1	1446	1638	13.27
Exp_2	1296	1554	19.90
Exp_3	1092	1584	45.05
Exp_4	1374	1596	16.15
Exp_5	1320	1584	20
Exp_6	1320	1542	16.81
Exp_7	1404	1494	6.41
Exp_8	1206	1500	24.37
Exp_9	1350	1554	15.11
Exp_10	1380	1512	9.56

Table 2

First 10 Result Experiments of Comparison Between AAC Method Against FCFS Batching Strategy in Three-Depots Warehouses for 60 Orders

Experiment number	AAC with three-depots	FCFS with three-depots	% difference
Exp_1	1920	2256	17.50
Exp_2	1746	2256	29.21
Exp_3	2064	2148	4.07
Exp_4	2040	2256	10.59
Exp_5	1986	2436	22.66
Exp_6	1764	2214	25.51
Exp_7	2040	2478	21.47
Exp_8	1914	2202	15.05
Exp_9	1860	2424	30.32
Exp_10	1848	2172	17.53

The second group of analysis is conducted to analyze the aggregate benefit of using AAC method by constructing multiple depots against FCFS strategy with one left-most located depot. The first 10 results of these 40 experiments are given in Table 3, and Table 4 for 40, and 60 order groups, respectively. The mean percentage differences obtained from the 40 experiments are 19.94%, and 20.12% for the 40, and 60 order groups, respectively. Based on these results, it can be said that constructing multiple depots has little impact when compared to the effect of AAC method for order batching, especially for small number of customer orders. But when the number of orders handled increases, it is expected that the aggregate effect of the AAC method and multiple depots can increase. As in the first analysis group, it can be concluded that the effect of AAC method for order batching can be significantly increased by constructing multiple depots for e-commerce warehouses where a hundred customer orders arrive hourly.

Table 3

First 10 Experiment Results of Comparison Between AAC Method with Three-Depots Against FCFS Strategy with One Left-Most Located Depot for 40 Orders

Experiment number	AAC with three-depots	FCFS with one left-most located depot	% difference
Exp_1	1446	1638	13.28
Exp_2	1296	1554	19.91
Exp_3	1092	1596	46.15
Exp_4	1374	1596	16.16
Exp_5	1320	1584	20
Exp_6	1320	1554	17.73
Exp_7	1404	1512	7.69
Exp_8	1206	1488	23.38
Exp_9	1350	1554	15.11
Exp_10	1380	1500	8.70

Table 4

First 10 experiment results of comparison between AAC method with three-depots against FCFS strategy with one left-most located depot for 60 orders

Experiment number	AAC with three-depots	FCFS with one left-most located depot	% difference
Exp_1	1920	2256	17.50
Exp_2	1746	2220	27.15
Exp_3	2064	2172	5.23
Exp_4	2040	2244	10
Exp_5	1986	2436	22.66
Exp_6	1764	2202	24.83
Exp_7	2040	2478	21.47
Exp_8	1914	2214	15.67
Exp_9	1860	2436	30.97
Exp_10	1848	2184	18.18

The last group of experiment is conducted to show the significance of depot position effect on total order picking distance. For this purpose, AAC algorithm is applied to two different warehouse layouts with two-depots that are located at the beginning of aisles 2 and 7, and warehouse layout with three-depots that are located at the beginning of aisles 1, 4, and 8. For three-depots layout, Depot-1 and Depot-8 are selected because of symmetry and Depot-4 is selected as the central depot. The first 10 results of 40 experiments are given in Table 5, and Table 6 for 40, and 60 order groups, respectively. The mean percentage differences obtained from the 40 experiments are 5.55%, and 5.57% for the 40, and 60 order groups, respectively. Based on these results, it can be said that constructing three-depots is more beneficial than two-depots situation.

Table 5

First 10 Experiment Results of Comparison Between AAC Method with Three-Depots Against AAC Method for Two-Depots for 40 Orders

Experiment number	AAC with three-depots	AAC with two-depots	% difference
Exp_1	1446	1632	12.86
Exp_2	1296	1470	13.43
Exp_3	1092	1260	15.38
Exp_4	1374	1524	10.92
Exp_5	1320	1398	5.91
Exp_6	1320	1410	6.82
Exp_7	1404	1440	2.56
Exp_8	1206	1314	8.96
Exp_9	1350	1320	-2.22
Exp_10	1380	1272	-7.83

Table 6

First 10 Experiment Results of Comparison Between AAC Method with Three-Depots Against AAC Method for Two-Depots for 60 Orders

Experiment number	AAC with three-depots	AAC with two-depots	% difference
Exp_1	1920	1992	3.75
Exp_2	1746	1962	12.37
Exp_3	2064	2148	4.07
Exp_4	2040	1938	-5.00
Exp_5	1986	2022	1.81
Exp_6	1764	1902	7.82
Exp_7	2040	1950	-4.41
Exp_8	1914	1932	0.94
Exp_9	1860	2064	10.97
Exp_10	1848	2106	13.96

As Gülyeşil and Durmuşoğlu (2024) explained, the multiple depots situation can be considered as a transition between warehouse layout where single left-most located depot and system that utilizing conveyor belts. Setting up conveyor belt and other necessary technological equipment can be particularly cost for medium-sized warehouses. These companies can improve order picking process by including multiple depots rather than bearing this high investment cost. In the literature, Tran-Vo et al. (2022) proposed mathematical model for small-sized problems to solve considered problem. On the other hand, a constructive heuristic algorithm is suggested in this study to handle large-sized problems.

5. Conclusion

In this study, order batching, depot selection and assignment problems are handled in multiple depots and multiple pickers considerations. To solve the mentioned problem, a new heuristic algorithm, AAC, is proposed and 320 experiments are conducted from different perspectives. Firstly, to demonstrate the performance of AAC algorithm on order batching problem, FCFS order batching method is used as comparison method. In this comparison, FCFS approach and AAC algorithm are employed for the warehouse layout with three-depots. In the second perspective, to analyze the combined effect of AAC method and constructing multiple depots, FCFS approach is applied for warehouse layout with single left-most located depot. Finally, to analyze the effect of depot position on total order picking distance, AAC algorithm is applied to warehouse layout with two-depots called Depot-2 and Depot-7 and warehouse layout with three-depots located at the beginning of aisles 1, 4, and 8. At the end of the experiments, it is concluded that constructing multiple depots has a positive impact on reducing total order picking distance. On the other hand, the selected order batching strategy has more importance on the total order picking distance compared to the constructing multiple depots strategy. Therefore, practitioners can focus on selecting effective order batching strategies to increase efficiency of order picking operation. As a conclusion, this research contributes to the warehouse management literature by addressing the relatively rare studied of multiple depots and multiple pickers situation. It also considers workload balance between order pickers employed in a depot. In addition to this, the proposed heuristic does not require the determination of important parameter values as in other algorithms. Therefore, it is especially significant for practitioners and easily applicable in real world business warehouses. For future studies, the cost of constructing multiple depots against reduction in total order picking distance can be analyzed. Also, proposed heuristic algorithm can be applied with other routing heuristic algorithms such as largest gap, midpoint, combined etc.

Author Contributions

In this study, Selma GÜLYEŞİL contributed to the conceptualization, development of the methodology, and original draft writing and Zeynep Didem UNUTMAZ DURMUŞOĞLU contributed to the supervision, original draft writing, and writing review and editing.

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Disclosure Statement

The authors declare that they have no competing interests.

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