APPLICATION OF MODIFIED COMBINED HEURISTIC TO REDUCE ORDER PICKING TOUR LENGTH IN CEVA XNZ WAREHOUSE

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ABSTRACT

This study focuses on the improvement of order sequencing to reduce length of picking tour in CEVA XNZ warehouse. The current sequencing method forces the picker to make a lot of backtracking and take longer paths when picking from the warehouse during order extraction. This author identifies that backtracking movement to occur in 43.281% of all order fulfillment cases in April 2013. To improve on the order sequencing method in CEVA XNZ, this author proposes application of a modified block heuristic that suits the warehouse configuration. Upon running the proposed method on all order picking completion cases in April 2013, it is found that the new method performs better in that it produces shorter picking tour length compared to the current method. The proposed method succeeds in reducing total picking tour length by 36.64%. On average the proposed method reduces length of an order picking case tour by 36.04%. Implementation of this method requires CEVA XNZ to take 3 measures: incorporate instruction in their issued order list and introduce 2 new location concepts to the pickers. It also has to integrate an order sequencing program in order list generation process.

Keywords: sequencing, reduce length, longer paths, modified, block heuristic, implementation
CHAPTER I
INTRODUCTION

1.1 Problem Background
Logistics is defined as the planning, organization, and control of all activities in the material flow, from raw material until final consumption and reverse flows of the manufactured product, with the aim of satisfying the customer’s and other interested parties’ needs and wishes (Jonsson and Mattsson, 2005). The resources are not limited to physical items but also include intangible or abstract items like information or time. Logistics is now commonly understood as a part of supply chain management. For globally-operating companies, the logistics function may be too much to be handled in-house since the supply chain scope usually spans across the globe. This idea gave birth to third party logistics.

Third party logistics (3PL) are services provided by logistics service provider that consists of logistics activities such as transportation, inventory management, item tracking, and value added services like secondary assembly (Sweeney and Evangelista, 2005). Warehouse and inventory management is a part of logistics operation. This involves storing and tracking goods within the 3PL’s storage unit (not the client’s). This warehouse may serve only as resource overflow storage or as a distribution point where the items are issued to retailers. As such, the core functions at a 3PL warehouse include receiving, inventory management, and shipping.

CEVA Logistics is one of the leading multinational 3PL companies in the world. The majority of its shares are owned by Apollo Global Management, an American private equity firm. Their facilities employ over 49000 manpower worldwide and reside in over 160 countries including Indonesia. CEVA was established in Indonesia as TNT Logistics in 1995, before its merger in 2007. In 2012, Indonesia won the CEVA Country of the Year awards. The CEVA XNZ warehouse (XNZ, a cosmetic company, is one of CEVA’s client in Indonesia) won the Best Site award.
for its rapid improvement within a short period and the high operational standards. Even so, there is still a lot of room for improvement. An interesting case is the order picking sequencing problem.

Currently, CEVA uses batch picking policy, where pickers are issued order lists containing a number of item orders that has to be extracted/picked from extraction points in one trip. The orders are sorted by racking location and the pickers have to follow the picking sequence when completing orders. The columns are letter-coded from right to left and the slots in a column are numbered from top (back of the warehouse) to bottom (front of the warehouse). There are some flaws with this sequencing/sorting method. First, most aisles contain 2 rows of racking (to the right and left of the aisles). Having the orders sorted by racking location means that the pickers have to finish picking from one side before they can pick from the other side. The diagram below will help illustrate the event.

![Diagram](image)

**Figure 1.1 Typical pick-path of aisle picking in CEVA XNZ warehouse**
The letters (A, B) mark the racking code and the numbers (1-14) represent the pick slot position within the racking. Take 8 extraction points: A1, A4, A5, A8, B4, B7, B10, and B12. As seen in the diagram above, this order sequence forces the picker to return up the aisle, creating additional length to complete picking within an aisle. The following diagram compares the vertical route length if the pick slots are extracted from as the picker traverse the pick aisle and the above diagram’s route length, with the length of backtracking highlighted in red.

It can be seen from the above diagram that the current order picking sequence results in longer picking route. This makes the total tour length between the first and last pick within an aisle equals to the vertical distance between the farthest pick slots plus the length of backtracking. Between April 1\(^{st}\) and April 30\(^{th}\) 2013, this backtracking issue occurs in 43.281\% of all order completion activities.
Another problem with the way current order list is sorted is that at any aisle, picking always start at the “highest” location, no matter where it is entered from. To understand the issue better, observe the following diagram given an order list of B9, B14, D2, D5, and D13.

![Diagram showing typical multiple aisle picking tour in CEVA XNZ warehouse]

As seen above, when the picker exits the right subaisle and enters the next, he/she does not start picking from D13 up to D2. Instead, the picker starts picking from the highest location and works his/her way down. It can be clearly seen that the resulting tour is not efficient and there is a way to improve this. In short, the current sequencing does not tap into the potential creating shorter picking tour. Ultimately, a method to sort the order list in a way that the problems above can be addressed and tackled is required. Success in determining and applying the method can reduce travel distance involved in picking.
1.2 Problem Identification and Statement

The background of the problem explained above leads to these statements:

- What order sequencing method can be utilized to reduce travel distance?
- How would the new method fare compared to the current method?
- How can the new method be applied?

1.3 Objective

The main objective this study is to determine a routing/sequencing method that creates a more efficient order picking tour compared to the one currently utilized in CEVA XNZ. This can be achieved by applying or developing a pick-path heuristic that will yield a more efficient picking tour given an order list. The author expects the complete analysis and result of this study can be utilized to:

- Increase operational productivity of a warehouse, particularly in picking operations
- Help in reducing probability of product mishandling with the shortened distance of material movement.

1.4 Scope and Limitations

Due to limitations of time and other resources, the scope and limitations of this study are:

- The evaluated data are dated between April 1\textsuperscript{st} and 30\textsuperscript{th} 2013.
- The study is limited to ground level racking where the picking activity occurs.

1.5 Assumptions

Some assumptions are made for the study to be interpreted on:

- Every order list can be completed in one trip
- Pickers can change directions within a pick aisle
- The width of pick aisles allows pickers to pick from both sides without changing position significantly.
• The pickers have positional awareness and complete knowledge of the warehouse/racking layout.

1.6 Final Project Outline

Chapter I Introduction
This chapter consists of problem background, problem identification and statement, scope and limitations of study, research benefit, and assumptions of the study.

Chapter II Literature Study
This chapter contains the explanation on order picking operations and pick-path heuristics, along with various examples and studies on development/modification of pick-path heuristics. It also contains explanation on tools used to support this study.

Chapter III Research Methodology
The overview on flow and framework of this study is explained here.

Chapter IV Data Collection and Analysis
This chapter contains the necessary data required to carry out the study. Here the performance of both current and proposed method are calculated and then compared. An analysis is provided to determine the success of proposed method, along with suggestions for proposed method application.

Chapter V Conclusion and Recommendation
The conclusion of this study is presented in this chapter, along with recommendations for future research.

This chapter contains the basis of this research, the intended purpose of study, the constraints to keep the study focused, and the way research is structured. The theories, references, and the previous studies that support this research are presented in the following chapter.
2.1 Order Picking Operations

Order picking is one of the activities/processes in a logistic warehouse. It consists of extracting items in specified quantities from their respective storage locations, which will then be shipped to ordering customers. It is one of the most highlighted processes in a logistic warehouse as it is the most costly process (Tompkins et al., 1996).

![Figure 2.1 Typical distribution of warehouse operating expense](image)

(Source: Tompkins et al., 1996)

Basically, picking activities consists of 4 main elements:

- Setup: Preparing of all the equipments required for picking purposes, such as forklift, hand pallet, check list, stationery, or scanner
- Travel: Movement by picker to go from or to extraction points
- Search: Identifying and pinpointing the exact storage/pick locations
- Pick: The act of item extraction from storage/pick locations to material transport equipment.
There are also some minor elements that complement the 4 main activities should they be necessary, such as documentation (of transaction), sorting, packing, and counting.

Travelling, or travel, is the largest element of labor in a typical distribution center (Bartholdi and Hackman, 2011). Travelling is a direct expense and waste to warehouse operations because it spends labor time but does not contribute to the warehouse’s throughput. Travelling typically takes about 50% percent of an order picker’s time (Tompkins et al., 1996).

![Bar chart showing the typical distribution of an order picker’s time](Source: Tompkins et al., 1996)

**Figure 2.2 Typical distribution of an order picker’s time**

### 2.2 Travel Distance Reduction

As previously stated, travelling generally makes up half of an order picker’s time, possibly more. This puts travelling problem to light, making its improvement the highest priority in order picking operations. One possible method is implementing a system in which a picker can extract items from a stationary extraction point. This is called stock-to-picker system, with which items or “stock” situated in a mechanical racking would be brought toward pickers. This eliminates the need for a picker to travel towards storage locations.
However, there are a few reasons that may put off a warehouse manager from using stock-to-picker system. Investments, maintenance expenses, and the necessary manpower to carry out/supervise that level operational sophistication are also major consideration in implementing the stock-to-picker system. Moreover, transition from manual to automated storage in an established warehouse can take a long time and disrupt the warehouse’s activities, greatly reducing its productivity during transition period. Also, as theoretically common and ideal as it is, that kind of technology may not be readily available within the country where the warehouse operates.

Where stock-to-picker system is not a common technology and its procurement is infeasible, a more logical improvement option is reducing/minimizing, rather than eliminating, picker movement as cost of traveling. There are several approaches that can be identified to do this: storage assignment, order batching, and order picking sequencing.

2.2.1 Storage Assignment

Basically, storage assigning principle calls for placing items in correct storage locations for the purpose of improving warehouse performance. This approach can improve not only travel time during picking but also space utilization and even put away (moving items from receiving to storage) time. Rouwenhorst et al. (2000) identified several types of storage assignment policy: random storage, closest open location storage, dedicated storage, class-based storage, and family grouping. Several studies have been conducted to compare the effectiveness of these policies. Tsige (2013) compared the performance of three storage assignment policies: random storage, class-based storage, and family grouping. Methods can also be combined to yield a more detailed analysis, one example being the combination of ELECTRE TRI method with ABC analysis by Fontana and Cavalcante (2011).
2.2.2 Order Batching

The idea of order batching is clustering single orders into batches in a way that the resulting picking tour formed will be efficient, as different order batching yields different picking tour length. By determining optimum order batching, efficient order picking tour can be obtained. There are various studies on different methods of order batching. Some examples include the modification of various off-line order batching heuristic approaches for on-line batching problem by Henn (2009) and the use of genetic-algorithm based order batching method (GABM) by Hsu et al. (2004)

2.2.3 Order Picking Sequencing

Order picking sequencing is an approach to order picking improvement aimed to reduce travel distance. The idea is to arrange a given picking list to produce and efficient picking tour with reduced total travel distance. Ratliff and Rosenthal (1983) presented an algorithm to produce order picking sequence and route in a rectangular warehouse with cross aisles in the front and back of the warehouse. Roodbergen and de Koster (2001) compared several routing heuristics in a rectangular warehouse with more than two cross aisles. Ertek et al. (2007) modified aisle-by-aisle heuristic by Vaughan and Petersen (1999) to analyze the impact of cross aisles. Some studies combined order batching method with order picking sequencing. Hong et al. (2012) proposed an integrated batching and sequencing method called indexed batching method (IBM) to solve narrow-aisle batch picking problem with consideration on blocking/congestion. Chan and Cheng (2012) proposed a two-phase hybrid algorithm that addresses batching and sequencing problem using particle swarm optimization (PSO) and ant colony optimization (ACO) algorithm.

The following table contains some of the previous studies similar to this study. This table lists and compares the goals, study platform, and methods conceived during the studies. It also explains whether the resulting methods permit aisle revisiting. It helps in understanding the position of current research and whether this research utilized appropriate order picking sequencing method.
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<tr>
<td></td>
<td>Developing method to create efficient picking tour in rectangular warehouse with two cross aisles</td>
<td>Analyzing the impact of cross aisles in a warehouse</td>
<td>Comparing performance of pre-existing heuristics with a developed branch-and-bound algorithm based heuristic</td>
<td>Applying modified combined heuristic to improve order picking sequencing in CEVA XNZ</td>
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<tr>
<td>Platform</td>
<td>Rectangular warehouse with two cross aisles</td>
<td>Rectangular warehouse with two or more cross aisles</td>
<td>Rectangular warehouse with two or more cross aisles</td>
<td>Rectangular warehouse with three cross aisles</td>
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<td>Conceived Method</td>
<td>Graph-based algorithm</td>
<td>Modification of aisle-by-aisle heuristic by Vaughan and Petersen (1999) for warehouse with unevenly spaces cross aisles</td>
<td>Dynamic programming based heuristic with extension for multiple cross aisle warehouse application (combined and ( combined^+ ) heuristic)</td>
<td>Modification of combined heuristic by Roodbergen and de Koster (2001) for CEVA XNZ warehouse</td>
</tr>
<tr>
<td>Permits Aisle Revisiting</td>
<td>Yes</td>
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Table 2.1 State of the art
2.3 Warehouse Layout

This study considers a rectangular warehouse with more than two cross aisles as the layout with which the heuristics will be simulated on. Two cross aisles are located in the front and back, with the additional cross aisles positioned across the racking, dividing the warehouse into blocks. The cross aisles can be used to change aisles and between blocks. The warehouse contains a number of parallel pick aisles. Each block contains a number of a part of pick aisles called subaisles (Roodbergen and de Koster, 2001).

![Diagram of warehouse layout](image)

(Source: Roodbergen and de Koster, 2001)

**Figure 2.3 An example of warehouse with more than two cross aisles**

The assumption generally used for studies on order picking heuristics in a warehouse with this configuration is that pickers retrieve items from the center of a pick aisle/subaisle, and the aisle width helps pickers to pick from both sides without changing position significantly yet also allows them to change directions comfortably within a pick aisle or subaisle.
2.4 Routing Heuristics
Roodbergen and de Koster (2001) presented five different routing heuristics in their paper: S-shaped heuristic, largest gap heuristic, aisle-by-aisle heuristic, and two heuristics they developed, combined heuristic and its improvement, \textit{combined}⁺ heuristic. The performances of these heuristics are compared in a rectangular warehouse with more than two cross aisles, with some of those heuristics usually reserved for two-cross aisles rectangular warehouse being modified so their use can be extended. These five heuristics can be distinguished into two categories, indicated by Theys \textit{et al.} (2009): block heuristic and lateral heuristic.

2.4.1 Block Heuristics
According to Theys \textit{et al.} (2009), block heuristics create block-by-block picking tour starting from the farthest block from depot containing at least one pick location to the nearest one. S-shaped, largest gap, combined, and \textit{combined}⁺ are considered block heuristics.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{block heuristic.png}
\caption{Block heuristic’s picker movement scheme}
\end{figure}
Figure 2.4 shows the picker movement scheme for block heuristics, assuming picking starts and ends in the depot and all blocks contain at least one pick. Note that the arrows do not signify the route that pickers will walk through but the sequences of visit the picker will take.

S-shaped, largest gap, and combined heuristics share the same rule for picker movement between blocks. First, a picker traverses the leftmost pick aisle to reach the front of the farthest block that contains at least one pick (1). Any picks passed during the trip are picked. Upon arrival, the picker then enters the block to complete picking within that block using the pre-determined heuristic. The picking tour within a block must end in the front of it (2). From there, the picker determines the leftmost and rightmost subaisle in the next block that contains at least one pick and enters the closest one (3) and continue picking in that block. After the picking in that block is done and there is no more block containing any picks, return to depot (4).

Figure 2.5 Example of block heuristic picking tour
Explanations on S-shaped, largest gap, and combined heuristics will focus on the way it shapes the picking tour within a block.

### 2.4.1.1 S-shaped Heuristic

S-shaped heuristic demands any subaisle in a block containing at least one pick location to be traversed completely through the entire length (Roodbergen and de Koster, 2001). Subaisles that do not contain any pick locations are not entered. If the last subaisle within a block is entered from the front, that subaisle is not traversed in its entirety and the picker has to return to the subaisle entrance after retrieving items from the farthest pick location.

![Figure 2.6 Example of S-shaped heuristic picking tour in a block](image)

### 2.4.1.2 Largest Gap Heuristic

Largest gap is defined in Roodbergen and de Koster (2001) as “the distance between any two adjacent pick locations within a subaisle, or between a cross aisle and the nearest pick location. Basically, in largest gap heuristic a block is divided into two parts of the same length: the front half and the back half. A subaisle entered from the front is traversed as far as the length of the front half (should a pick location exist on its far end). The same goes for the back half if a subaisle is entered from the rear.
If picking starts at the front of a block, first the picker travels through the leftmost subaisle that contains at least one pick location entirely. After reaching the back of the block, the picker travels along the cross aisle and picks items from the back half by entering the subaisles one by one as needed. Upon reaching the last subaisle with pick locations, the picker traverses its entirety from the rear and exits from the front. At this point, the picker then travels along cross aisle again to retrieve items from pick locations in the front half by entering the subaisles as necessary. The picker moves to the next block after all the items in that block are picked.

**Figure 2.7 Example of largest gap picking tour in a block**

### 2.4.1.3 Combined Heuristic

Combined heuristic was developed by Roodbergen and de Koster (2001). This heuristic utilizes dynamic programming method to create an order picking tour. This heuristic does not allow backtracking, meaning that each aisles can be visited only once and picking within a block must be completed from leftmost subaisle containing at least one pick location to the rightmost or vice versa. All possible picking tours that abide by the rule are assessed to find the shortest picking tour.

To setup the platform for applying combined heuristic, first the elements are denoted. In this case, the number of blocks are defined as \( k \) and the number of pick aisles/subaisles as \( n \). Notation \( i \) represents block \((i = 1, 2, \ldots, k)\) and
notation \( j \) represents pick aisles/subaisles \((j = 1, 2, ..., n)\). Some physical locations are also given notation:

- \( a_{ij} \): The back end of a subaisle \( j \) in block \( i \).
- \( b_{ij} \): The front end of a subaisle \( j \) in block \( i \).
- \( l \): First pick aisle containing at least one pick location
- \( r \): Last pick aisle containing at least one pick location

Order picking tour starts from the left/rightmost subaisle that contains at least one pick location and ends at the farthest subaisle that contains at least one pick location. Partial route within that visits all pick locations from the starting point to subaisle \( j \) is denoted as \( L_j \). The partial route can be classified into two:

- \( L_j^a \): Partial tour that ends at the back of subaisle \( j \).
- \( L_j^b \): Partial tour that ends at the front of subaisle \( j \).

Next, transitions are denoted. Transition is a single set of movement that can be taken by picker and combinations of them make up partial route. Transitions to move from the entrance of one subaisle to the next \((j - 1 \text{ to } j)\) can be classified into two:

- \( t_a \): The transition between subaisles that happens along the back of the block.
- \( t_b \): The transition between subaisles that happens along the front of the block.

Transitions to pick items in a subaisle are also denoted to distinguish them from each other. There are four possible transitions:

- \( t_1 \): The subaisle is traversed in its entirety and exited on the other end.
- \( t_2 \): The subaisle is not entered and skipped. This is taken if a subaisle does not contain any pick locations.
- \( t_3 \): The subaisle is entered and exited from the front of the block.
- \( t_4 \): The subaisle is entered and exited from the back of the block.
The length of partial route $L_j$ is equal to the partial route length of up to previous subaisle $L_{j-1}$ plus transition $t_w$, or

\[(L_j = L_{j-1} + t_w)\]  

(2-1)

The notation $w$ represents the type of transition taken ($w = 1, 2, 3, 4, a, b$) (Roodbergen and de Koster, 2001). Though written as a single transition, value of $t_w$ is generally the sum of 2 transitions: a “subaisle” transition ($t_1, t_2, t_3, t_4$) and a “cross aisle” transition ($t_2, t_b$), except in front of a subaisle without any pick locations during which the picker then moves on to the next subaisle (though transition $t_2$ exists, it can be omitted from the notation as its value = 0) and on the last subaisle where it consists of only $t_1$ or $t_3$ (picking tour has to end in front of the block and there are no more subaisles to move to). Partial routes within a block are constructed using potential states, possible transitions, and the costs of making the transitions (Roodbergen and de Koster, 2001). There are several steps in constructing the partial routes with dynamic programming:
• Step 1: Consider a block \( i \) that contains pick locations. The picker is located at the front end of the block \( i \). Two partial routes can be considered to retrieve items in the nearest/first subaisle:
  
  o \( L^a_i \), starting at the at the front \( (b_{ii}) \) and ends at the back \( (a_{ii}) \) using \( t_1 \).
  
  o \( L^b_i \), starting at and ending at the front \( (b_{ii}) \) using \( t_3 \).

If picking tour starts from the back of the block \( i \), the two partial routes become:

  o \( L^a_i \), starting at and ending at the front \( (a_{ii}) \) using \( t_4 \).
  
  o \( L^b_i \), starting at the at the front \( (b_{ii}) \) and ends at the back \( (a_{ii}) \) using \( t_1 \).

• Step 2: for each subsequent aisle leading to the last subaisle with at least one pick location, determine partial routes that ends at the back and front of the block \( (L^a_j \) and \( L^b_j \), respectively) using dynamic programming method:

\[
L^a_j = \begin{cases} 
L^a_{j-1} + t_a + t_4 & (\text{if } L^a_{j-1} + t_a + t_4 < L^b_{j-1} + t_b + t_1) \\
L^b_{j-1} + t_b + t_1 & (\text{otherwise})
\end{cases}
\]  

(2-2)

and

\[
L^b_j = \begin{cases} 
L^a_{j-1} + t_a + t_1 & (\text{if } L^a_{j-1} + t_a + t_1 < L^b_{j-1} + t_b + t_3) \\
L^b_{j-1} + t_b + t_3 & (\text{otherwise})
\end{cases}
\]  

(2-3)

If subaisle \( j \) does not contain any pick locations, the partial routes become:

\[
L^a_j = L^a_{j-1} + t_a
\]  

(2-4)

and

\[
L^b_j = L^b_{j-1} + t_b
\]  

(2-5)
• Step 3: The last subaisle with at least one pick location (subaisle \( l \)) is visited. Since the resulting route must end in front of the block, the partial routes in subaisle \( r \) become:

\[
L_r^b = \begin{cases} 
L_r^{a-1} + t_a + t_1 & \text{(if } L_r^{a-1} + t_a + t_1 < L_r^{b-1} + t_b + t_3) \\
L_r^{b-1} + t_b + t_3 & \text{(otherwise)}
\end{cases} \tag{2-6}
\]

\( L_r^b \) becomes the partial picking tour of block \( i \).

The following is an example of combined heuristic tour construction. Consider a block \( i \) with four subaisles and 16 pick slots per subaisle (8 on each side). The block contains 10 pick locations. Each subaisle measures 9 meters when traversed entirely from the center of the cross aisle on one end to the other. Distance between pick slots is measured 1 m, and the distance from the outmost pick slot to the center of the nearest cross aisle is also 1 m. The distance between adjacent subaisle entrances is 4 m. The following diagram illustrates the map for picking purposes, with nodes representing pick locations and subaisle entrances and lines representing paths traversable by pickers. Distances between pick locations (in meters) are also included to assist in interpretation of the diagram.

![Figure 2.9 Possible route and transition map in block i](image-url)
Picking starts at the bottom of the leftmost subaisle, or node $b_{i1}$. At this point, there are two possible partial routes:

- $L^a_1 = t_1 = 9 \text{ m}$
- $L^b_1 = t_3 = 2 \times 2 = 4 \text{ m}$

Now there are two possibilities each for $L^a_2$ and $L^b_2$, totaling in four possible partial routes:

- $L^a_2 \{ L^a_1 + t_a + t_4 = 9 + 4 + (2 \times 6) = 25 \text{ m} \}$
- $L^b_2 \{ L^b_1 + t_b + t_1 = 4 + 4 + 9 = 17 \text{ m} \}$
- $L^a_2 \{ L^a_1 + t_a + t_1 = 9 + 4 + 9 = 22 \text{ m} \}$
- $L^b_2 \{ L^b_1 + t_b + t_3 = 4 + 4 + (2 \times 8) = 24 \text{ m} \}$

For each $L^a_2$ and $L^b_2$, the shorter partial route is chosen. This results in $L^a_2 = L^b_1 + t_b + t_1$ and $L^b_2 = L^a_1 + t_a + t_1$. For the next subaisle ($j = 3$) does not contain any pick locations, therefore:

- $L^a_3 = L^a_2 + t_a = 17 + 4 = 21 \text{ m}$
- $L^b_3 = L^b_2 + t_b = 22 + 4 = 25 \text{ m}$

For the last subaisle ($r = 4$) there are only two possible partial routes, those of $L^a_4$. $L^a_4$ are not considered as the tour has to end in front of the block. The possible partial routes are:

- $L^a_4 \{ L^a_3 + t_a + t_1 = 21 + 4 + 9 = 34 \text{ m} \}$
- $L^b_4 \{ L^b_3 + t_b + t_3 = 25 + 4 + (2 \times 6) = 41 \text{ m} \}$

Out of these two routes the shorter one is chosen, making the final route $L^b_4 = L^a_3 + t_a + t_1$. The expansion of route construction for this partial route from starting point is $L^b_4 = t_3 + t_b + t_1 + t_a + t_a + t_1$. 
Note that the route is identified as partial as it is assumed that block $i$ is a part of a warehouse, and a full picking route can be identified when all pick locations within the warehouse are addressed.

2.4.1.4 Combined$^+$ Heuristic

The use of dynamic programming in for route construction within block in this heuristic is the same as the combined heuristic, but the combined$^+$ offers a few improvements from combined heuristic on a warehouse scale.

Combined$^+$ heuristic force pickers to enter the last/nearest block from the farthest subaisle containing at least one pick location, and work his/her way toward the subaisle nearest to depot. This is because if said block is entered from the closer subaisle to depot, (as it is possible in combined heuristic), the picker would end the tour in the far end of the block, and has to travel back along the front cross aisle, taking the horizontal distance already covered during picking, to reach the depot. By forcing the picker to enter from the farthest subaisle, the resulting travel distance of partial route in that block can be decreased, and at most it stays the same (Roodbergen and de Koster, 2001).
Also, combined\textsuperscript{+} heuristic addresses the possibility of dynamic programming application in determining a picker’s route from depot to the farthest block containing pick locations. Basically, the trip could visit one or more subaisles containing pick locations in the blocks leading to the farthest, reducing the number of subaisles that have to be considered during partial route construction in those blocks later on. This results in full picking route that is at most as long as the route generated using combined heuristic. The following diagram shows the routes produced by combined and combined\textsuperscript{+} in the same case of picking route problem.

![Diagram showing routes produced by combined heuristic (left) and combined\textsuperscript{+} heuristic (right).](Source: Roodbergen and de Koster, 2001)

**Figure 2.11 Routes produced by combined heuristic (left) and combined\textsuperscript{+} heuristic (right)**

### 2.4.2 Lateral Heuristic

Lateral heuristics are order picking heuristics that complete orders in a pick aisle-by-pick aisle manner, where pickers would have to finish picking within one pick aisle before moving to the next (Theys et al., 2009). Out the five heuristics compared by Roodbergen and de Koster (2001), only aisle-by-aisle heuristic falls to lateral heuristic category. The following are the picker movement schemes for
lateral heuristics, assuming picking starts and ends in the depot and all pick aisles contain at least one pick.

![Lateral heuristic’s picker movement scheme](image)

**Figure 2.12 Lateral heuristic’s picker movement scheme**

Note that the arrows do not signify the route that pickers will walk through but the sequences of visit the picker will take. Aisle-by-aisle heuristic discussed by Roodbergen and de Koster (2001) was previously presented by Vaughan and Petersen (1999). Ertek et al. (2007) constructed a model for this heuristic. With this heuristic, every pick aisle up to the farthest that contains at least one pick location is visited. The route is constructed using dynamic heuristic to find out which cross aisle has to be traversed to get to the next pick aisle.

The route starts at the depot and ends in the front cross aisle of the farthest pick aisle that contains at least one pick locations. But depending on the configuration of the warehouse, the route may end on another point at the warehouse where the items are gathered or back at the starting point. Before constructing the picking
tour, the elements and variables involved are given notations, made with
assumption that the tour starts and end on the same depot:

- $P$: Number of pick aisles ($p = 1, 2, ..., P$)
- $d$: first pick aisle containing at least one pick
- $z$: last pick aisle containing at least one pick
- $e$: distance between the center of adjacent cross aisles
- $C$: Number of cross aisles ($c = 1, 2, ..., C$). The back cross aisle is cross
  aisle $c = 1$ and front cross aisle is cross aisle $c = C$
- $i$: Cross aisle where a pick aisle is entered from. $i = \begin{cases} C & \text{if } p = d \\ c & \text{otherwise} \end{cases}$
- $j$: Cross aisle where a pick aisle is exited from. $j = \begin{cases} C & \text{if } p = z \\ c & \text{otherwise} \end{cases}$
- $G_p$: Distance between depot and front cross aisle of pick aisle $p$.
- $U_p$: Distance between the highest and lowest pick location in pick aisle $p$
- $B1_p(i,j)$: Distance between the highest pick location to cross aisle
  $\min(i,j)$
- $B2_p(i,j)$: Distance between the highest pick location to cross aisle
  $\max(i,j)$
- $T$: Transition from pick aisle $p$ to $p + 1$ from cross aisle. The value of
  $T = \begin{cases} 0 & \text{if } p = d \\ e & \text{otherwise} \end{cases}$
- $A_p(i,j)$: Total distance to pick all the items in pick aisle $p$ and move to the
  next aisle if pick aisle $p$ is entered at $i$ and exited at $j$.
- $f_p(i)$: Shortest partial picking tour from the front cross aisle pick aisle $d$
  to pick aisle $p$ given it is entered from cross aisle $i$

The steps of route construction are as follows:

- Step 1: Starting from the depot, the picker travels to the front cross aisle
  pick aisle $d$ with path length

$$G_d = (d - 1) \times e \quad (2.7)$$

- Step 2: From this point, possible partial routes
\begin{equation}
A_p(i,j) = T + B_{1p}(i,j) + U_p + B_{2p}(i,j) \tag{2-8}
\end{equation}

are constructed for every \((i,j)\) combination, where:

- \(B_{1p}(i,j) = 0\) if cross aisle \(\text{min}(i,j)\) is positioned higher than the highest pick location in pick aisle \(p\) or pick aisle \(p\) does not contain any pick locations
- \(B_{2p}(i,j) = 0\) if cross aisle \(\text{max}(i,j)\) is positioned lower than the lowest pick location in pick aisle \(p\) or pick aisle \(p\) does not contain any pick locations.

Function \(f_p(i)\) is then used to determine the shortest partial tour up to pick aisle \(p\) if it is entered from cross aisle \(i\). The equation:

\begin{equation}
f_p(i) = \min_j \{A(i,j) + f_{p-1}(j)\} \tag{2-9}
\end{equation}

Is used to determine the shortest partial route up to pick aisle \(p\).

- Step 3: After all the items are picked and the picker has exited to the front of the warehouse, return to starting point with path length

\begin{equation}
G_z = (z - 1) \times e \tag{2-10}
\end{equation}

- Step 4: Construct full picking tour as \(G_d + f_m(i) + G_z\).
2.5 C-combined Heuristic

C-combined heuristic is a model developed specifically for this study. The model is based on combined heuristic by Roodbergen and de Koster (2001) with the addition of arbitrary block entering rule. The rule states that the last block containing at least one pick location must be entered from the subaisle farthest from depot. That way, the partial picking tour in this block would finish closer to depot, because the picker works his/her way towards depot as he/she complete the picking tour. This block entering rule is similar to that of $combined^+$ by Roodbergen and de Koster (2001). The difference between them is that C-combined heuristic does not incorporate added dynamic programming processes $combined^+$ has. C-combined heuristic is meant for use in rectangular warehouse with three cross aisle (front, back, and middle cross aisle), and application to other warehouse layout would require additional tweaking.
The references and platform for this study on order picking operations, order picking improvement, various approaches on travel distance reduction, and introduction to various heuristics has been established in this chapter. The following chapter explains the steps from start to finish.
CHAPTER III
RESEARCH METHODOLOGY

The following diagram illustrates the research framework of the study.

![Diagram of research framework]

**Initial Observation**
- Participate in order picking activity
- Observe order list

**Problem Identification**
- Analyze problems with order picking sequencing
- Determine problem statements
- Define objectives, scope, limitations, and assumptions

**Literature Study**
- Order picking activity
- Travel distance reduction approaches
- Warehouse layout
- Various routing heuristics

**Data Collection**
- Warehouse layout and measurements
- Order list detail of April 2013

**Current Method Model Interpretation and Tour Length Construction**
- Warehouse sectioning and numbering
- Routing definition
- Notation of elements
- Model interpretation
- Tour construction and length calculation

**Proposed Method Model Construction and Tour Length Construction**
- Warehouse sectioning and numbering
- Routing definition
- Notation of elements
- Model construction
- Tour construction and length calculation

Figure 3.1 Research framework diagram
3.1 Initial Observation
The study begins by observing the picking operations in CEVA XNZ warehouse. During the time the author spends there, the author participated in an order picking tour accompanied by a picker at work. As the author followed the path taken by the picker from one location to the next, the author realized that the picker did not visit the pick locations at both sides of an aisle in one go. Rather, the picker visited the locations one side first before tracking back up the path he had taken to pick from the other side. Upon inspecting the order list carried by the picker, it is found that the shape of picking tour he took is consistent with the way the orders within the order list are sorted.

3.2 Problem Identification
The current order list generation system in CEVA sorts the order according to their location in ascending manner. As most pick aisles contain two racking columns to pick from, this means that within a pick aisle a picker has to finish picking on one column of racking before moving to the other column. Figure 1.3 in Chapter 1 illustrates this case. On extreme cases, a picker would have to traverse the pick aisle completely to pick from one side, return to the beginning, and then re-traverse it to pick from the other side.
Moreover, due to this sorting, the picker must start picking at the farthest pick location from the front of the warehouse when he/she starts picking at the subsequent aisle. This means that even though the picker passed one or more pick locations along the way, the picker skipped them because they came later in the order list. Consequently, picking activities usually takes a lot of time because the pickers have to cover a considerable distance.

Drawing information from the identified issue, problem statements are declared. Research objective, scope, limitations, and assumptions are defined to provide the platform for the research to be conducted. Failure to set these constraints will complicate the study unnecessarily, making the study unfocused, and may even direct the study away from the intended purpose.

3.3 Literature Study
The necessary references are identified to support the study and provide background knowledge on methods and principles used in the study. Previous studies on the subject that are relevant to the study are also identified. This is crucial in determining the direction and procedures this author will take in completion of this study. The literature study contains explanation on order picking activity in a typical warehouse that serves as the platform of the study. A brief look into previous researches on travel distance reduction approaches and routing heuristics is also presented here as the reference for proposed method. The literature study is presented in chapter 2.

3.4 Data Collection
The data was collected during the author’s observation period in CEVA XNZ warehouse. While there were a lot of data this author obtained during that period, the necessary data for the purpose of this study are:

- CEVA XNZ warehouse layout and measurements of CEVA XNZ storage area
- Order list detail of April 2013 from shipping department, containing all order lists issued from April 1st to April 30th 2013.
3.5 Current Method Model Interpretation and Tour Length Calculation

As CEVA XNZ warehouse does not keep track of the picking tour length data, this study constructed a model to calculate the tour length resulted from current order picking sequencing. The foundations for this calculation are laid out: warehouse locations are numbered, the routing pattern resulting from current order sequencing is defined, elements are denoted, and then a model is build by interpreting the routing pattern.

3.5.1 Warehouse Sectioning and Numbering

In this step, the CEVA XNZ warehouse is sectioned and its locations are numbered as necessary to provide the platform for the model to construct picking tour of every order lists of April 2013.

3.5.2 Routing Definition

In this step, the routing pattern of current order sequencing is defined. An example of order picking problem is provided to give good illustration and visualization of this routing pattern. Each stage of the resulting picking tour and various cases are elaborated so that every possibility is addressed.

3.5.3 Notation of Elements

Prior to model interpretation, the elements and variables involved in calculation are denoted. The notation of elements in this step is only to be used for the resulting model, to avoid confusion.

3.5.4 Model Interpretation

A model is constructed based on the routing definition previously made. Since CEVA XNZ warehouse does not utilize any routing heuristic, this model interpretation is important to calculate the tour length for the order lists of April 2013. The model utilizes the notation of elements determined previously.
3.5.5 Tour construction and Length Calculation

Using the model constructed in the previous step, full picking tour is constructed for every order list. The length is also calculated. To give a thorough look on the tour construction, a demonstration is provided in chapter 4, based on one of the order lists.

3.6 Proposed Method Model Construction and Tour Length Calculation

The proposed order sequencing method is based on the combined heuristic by Roodbergen and de Koster (2001). The modified heuristic incorporates arbitrary block entering rule of combined by Roodbergen and de Koster (2001). This model for this heuristic borrows the notation of elements and block picking tour steps of combined heuristic, with addition of several elements to allow the model to construct full picking tour.

3.6.1 Warehouse Sectioning and Numbering

The CEVA XNZ warehouse layout is sectioned into blocks. This is necessary to create a platform for block heuristic tour constructions. Several new locations are defined and numbered to facilitate tour construction and length calculation.

3.6.2 Routing Definition

The routing pattern of full picking tour construction is defined as the basis for model construction. The same order picking problem used in routing definition of the current method is used here to give illustrations of the full picking tour at every stage. Elaboration of various cases is also provided to address every possibility.

3.6.3 Notation of Elements

Several elements are added and denoted to provide all the necessary variables required to construct full picking tour. Notation of elements for block picking tour is taken from combined heuristic.
3.6.4 Model Construction
In this step, the model for full picking tour of C-combined heuristic. The steps in block picking tour are taken from combined heuristic explained in literature study in chapter 2.

3.6.5 Tour Construction and Length Calculation
For every order list of April 2013 full picking tour is constructed and the length is calculated using C-combined heuristic model. A demonstration of thorough tour construction and length calculation is provided in chapter 4, using the same order list used in current method tour construction demonstration.

3.7 Comparison and Analysis
3.7.1 Comparison of Current and Proposed Method Performances
The resulting tour lengths of every order list for both methods are compared. The total and average tour lengths are compared, and the value of improvement C-combined heuristic succeeds in producing is determined. A brief analysis of the methods is also provided.

3.7.2 Suggestion of Proposed Method Implementation
In this step, measures are elaborated if CEVA XNZ warehouse is to implement the proposed method. The measures include proposal of new order list layout and integration of C-combined heuristic sequencing into order list generation process in CEVA XNZ warehouse.

3.8 Conclusion and Recommendation
The result of calculation, comparison and analysis is concluded in this chapter. The conclusions presented respond the problem statements. Recommendations are presented for future researches to take the study of order picking activity improvement in CEVA XNZ warehouse to the next step. Since utilization of the modified model is yet to be realized, recommendations for the company on its application are also provided.
3.9 Detailed Framework

The following is detailed framework of this study.

![Flowchart of Detailed Framework](image-url)

Figure 3.3 Detailed framework
The steps taken for this study has been explained here. The following chapter contains the collection of data along with calculation result of both current and proposed method. Other than that, comparison of method performance is also presented along with the analysis.
CHAPTER IV
CALCULATION AND ANALYSIS

4.1 Data Collection

4.1.1 Warehouse Layout Description and Measurements

The following is a detailed figure of CEVA XNZ warehouse layout.

![CEVA XNZ warehouse layout](image)

Figure 4.1 CEVA XNZ warehouse layout
The warehouse contains 14 columns of racking. 13 of them houses 58 pick slots and 1 contains 56 pick slots, totaling in 810 pick slots. The racking are separated in the middle by a cross aisle, dividing the warehouse into two blocks of different length. Each column in the top block is 32 slots long with the exception of column N which is 30 slots long. The length of bottom block is 26 slots, and each column in this block has the same length.

There are 8 pick aisles, 16 subaisles (2 blocks × 8 aisles) and 3 cross aisles in this layout. The pick aisles consists of 6 interior pick aisles and 2 exterior pick aisles on the far left and right. Because of their position, the exterior pick aisles have only one column of racking to pick from, while the interior pick aisles have two. The cross aisles do not have slots to pick from, and serves mainly for moving between pick aisles or blocks. For both heuristics, it is assumed that picker always walk right along the center of the path when traversing pick aisles or cross aisles.

The racking are letter-coded from right to left and numbered from top to bottom like the actual warehouse. The slots are numbered based on their position, not on the number of slots in the respective column. Thus, parallel slots share the same numbering even though column N has 2 less slots than the other columns. Originally, each racking is coded based on its column code (A-N), position number (1-58), and position from the ground. However, since this layout focuses on slots accessible by pickers (ground level slots), their names is only the combination of the column name and their position within the column (e.g. A7, F16). Picking starts and ends at the bottom right corner of the warehouse (the center of front cross aisle far right, in front of the rightmost pick aisle) in every heuristics. This point is shown in figure 4.2 as the small red circle with letter “S” on it. Immediately to its right is the shipping department/depot, where order lists are issued.

This warehouse measures 64 meters from the center of the front cross aisle to the center of back cross aisle. Each cross aisles is 3 meters wide and each pick aisles is 2 meters wide. It is assumed that no significant lateral movements are made
when a picker reaches for either side of a pick aisle during extraction. The distance between adjacent slots is 1 meter and the distance from the center of a cross aisle to the nearest slot is 2 meters. The distance between adjacent pick aisle openings is 4 meters. The following diagram gives an illustration on these measurements.

![Diagram of pick aisle dimensions](image)

**Figure 4.2** Measurement of cross aisle width, pick aisle width, distance adjacent between slots, distance between center cross aisle and the nearest slot, and distance between adjacent pick aisle openings

### 4.1.2 Order List Detail

There are 573 order lists issued to the pickers in April 2013, altogether containing a total of 32970 lines of order. The smallest order list size is 16 orders, with 59 of them are of this size. The biggest order list is order list no. 395714, which contains 145 orders. Complete order list detail can be seen in Appendix 1. The complete order list detail is divided into 3 parts:

- Order list: Information on order list number
- Size: The number of orders/pick locations in the respective order list
• Locations: pick locations of the orders, sorted by location code from left to right.

<table>
<thead>
<tr>
<th>Order List</th>
<th>Size</th>
<th>Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>382565</td>
<td>22</td>
<td>C3 E58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C6 E24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C12 C35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C14 C14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C22 C14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C24 C50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C32 C32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D24 D24</td>
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<td></td>
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<td>D20 D33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E9 E24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E26 E32</td>
</tr>
</tbody>
</table>

Figure 4.3 Information layout of Appendix 1

The above diagram shows how the information are laid out in Appendix 1.

4.2 Current Method Model Interpretation and Tour Length Calculation
4.2.1 Warehouse Sectioning and Numbering
The following diagram depicts the warehouse sectioning and numbering required for picking tour construction with current method.
The shape of picking tour resulted from current order picking sequencing CEVA XNZ utilized is similar to that of lateral heuristic. Therefore for this model, pick aisles are numbered from right to left (from the closest to the farthest from depot) and the cross aisles are numbered from top to bottom (from the farthest to the closest from depot). In short, this model platform extends the original warehouse sectioning and numbering by providing additional variables for tour construction using the model interpretation.

4.2.2 Current Method Routing Definition

CEVA XNZ currently does not employ any particular sequencing method. Their routing pattern is shaped by way of their order list sorting method system. Their lists are issued sorted based on the location of items in the list, in ascending
manner. In other words, orders are retrieved by column. Theoretically, in a pick aisle with several pick locations on both sides parallel to each other, a picker has to travel the pick aisle to retrieve items from one side then track back up his/her path to pick retrieve items on the other side.

Consider an order picking problem $X$ in figure 4.5. The warehouse is smaller compared to the CEVA XNZ warehouse layout depicted in figure 4.1, with fewer locations and pick aisles. It however has the same number of cross aisles. Picking starts at the shipping department, where the order lists are issued. From there, picker travels to the first pick location. Given the first pick is located in the upper block on pick aisle 2 or above, this can be done by walking along the front of the warehouse before entering the pick aisle containing the first pick, or by traversing the rightmost pick aisle, before turning into the middle cross aisle and entering the said pick aisle from there. Suppose the picker takes the most efficient route, difference in length between the two routes is non-existent. Figure 4.5 illustrates this case. Red circle represents where the route starts and blue circle represents the where it ends.
From this point, the picker starts retrieving all the items within the pick aisle. Since items are picked by column, there are 3 vertical lengths that make up the whole length of picking route within the aisle: distance from the highest to the lowest pick location on the right column, distance from the lowest pick location on the right column to the highest pick location on the left column, and distance from the highest to the lowest pick location on the left column. In case (1), the picker has to return to the upper block to pick aisle from the left column after retrieving all items on the right column. An aisle may contain picks only on the left column (2) or right column (3). In these cases, there is only one vertical length that makes up the aisle picking route, which is the distance between the highest and lowest pick location. If the lowest pick location on the right column is located higher than the highest pick location on the left column (4) the picker does not have to do any
backtracking and can simply continue traversing the aisle to pick aisle from the left column. Figure 4.6 illustrates these cases. Note that the horizontal lines do not represent added length, but simply indicating the picker is making a turn or picking from another column.

After all the items from the aisle are picked, the picker then moves to pick from the next aisle. Considering this layout, there are three ways to go to the next pick location on the next aisle: from the back cross aisle, from the middle cross aisle, or from the front cross aisle. For the purpose of this model, it assumed that the picker always takes the most efficient route to reach the next aisle. Dynamic programming can be used to find the shortest of the three routes. The following figure shows the possible routes, with the shortest one highlighted in green.
Figure 4.7 Three possible routes to move to next aisle. The shortest route is highlighted in green.

After picking from the last location, the picker returns to starting depot. If the last location is located in the farthest block, there are again two logical routes the picker can take upon exiting the block: travel along the middle cross aisle and down the rightmost pick aisle or go all the way to the front cross aisle and walk through it to reach depot. As with the case of getting to the first pick location
previously illustrated, the length of these two routes are basically the same. The following diagram illustrates the full picking tour of the order picking problem $X$.

Figure 4.8 Full picking tour of order picking problem $X$ with current routing pattern

The tour starts and ends on the red circle. The picker starts the tour up the first pick aisle from the front cross aisle and ends it through the front cross aisle from the bottom of the last pick aisle. The blue dots mark the points in the tour where the picker picks from the right column and the yellow dots mark where the picker picks from the left.

4.2.3 Notation of Elements
All the necessary elements to construct the model interpretation of this routing pattern are defined:
- $P$: Number of pick aisles ($p = 1, 2, ..., P$)
- $d$: first pick aisle containing at least one pick.
- $z$: last pick aisle containing at least one pick.
- $e$: distance between the center of adjacent cross aisles.
- $C$: Number of cross aisles ($c = 1, 2, ..., C$). The back cross aisle is cross aisle $c = 1$ and front cross aisle is cross aisle $c = C$.
- $i$: Cross aisle where a pick aisle is entered from. The value of $i = \begin{cases} C & \text{if } p = d \\ c & \text{otherwise} \end{cases}$
- $j$: Cross aisle where a pick aisle is exited from. The value of $j = \begin{cases} C & \text{if } p = z \\ c & \text{otherwise} \end{cases}$
- $G_p$: Distance between depot and front cross aisle of pick aisle $p$.
- $RQ_p$: The number of pick locations on the right column of pick aisle $p$.
- $LQ_p$: The number of pick locations on the left column of pick aisle $p$.
- $V^i_p$: Distance to first pick location in pick aisle $p$ if entered from cross aisle $i$.
- $W^j_p$: Distance to last pick location in pick aisle $p$ if exited from cross aisle $j$.
- $RC_p$: Distance between the highest and lowest pick location in the right column in pick aisle $p$. $RC_p = 0$ if the right column does not have any pick locations or has only one pick location.
- $LC_p$: Distance between the highest and lowest pick location in the left column of pick aisle $p$. $LC_p = 0$ if the left column does not have any pick locations or has only one pick location.
- $BT_p$: Distance between the lowest pick location of the first column and the highest pick location of the second column in pick aisle $P$.
- $T$: Transition from pick aisle $p - 1$ to $p$ from cross aisle $j$.
- $X_p(i, j)$: Total distance to pick all the items in pick aisle $p$ and move to the next aisle if pick aisle $p$ is entered at $i$ and exited at $j$. 
• $f_p(j)$: Shortest partial picking tour from the front cross aisle pick aisle $d$ to pick aisle $p$ given it is exited at cross aisle $j$

4.2.4 Current Method Model Interpretation

This model is established with assumption that the picker always enters pick aisle $d$ and exits pick aisle $z$ through the front cross aisle. The resulting full picking tour length this obtained from this heuristic is basically made up of three parts: The distance from depot to the front of pick aisle $d$; the partial picking tour length, total distance to pick all the items from pick aisle $d$ to $z$, and the distance from the front of pick aisle $z$ to the depot. As the current heuristic is a lateral heuristic, the steps of tour construction model is similar to that of aisle-by-aisle’s explained in chapter 2 section 2.4.2. The model for constructing this picking tour is as follows:

- Step 1: The picker travels from depot to the front of pick aisle $d$. The length of this path can be calculated using equation (2-7)
- Step 2: From pick aisle $d$ to $z$, calculate the length of partial picking tour to visit all pick aisles and pick all items with equation

$$X_p(i,j) = T + V^i_p + RC_p + BT_p + LC_p + W^j_p.$$  \hspace{1cm} (4-1)

Here are several conditions that affect the variables of $A_p(i,j)$:

- $T = \begin{cases} 0 & \text{if } p = k \\ e & \text{otherwise} \end{cases}$
- $RC_p = \begin{cases} 0 & \text{if } RQ_p \leq 1 \\ (value) & \text{if } RQ_p > 1 \end{cases}$
- $LC_p = \begin{cases} 0 & \text{if } LQ_p \leq 1 \\ (value) & \text{if } LQ_p > 1 \end{cases}$
- $BT_p = 0$ if $RC_p = 0$ or $LC_p = 0$
- $V^i_p = 0$ if $RQ_p = LQ_p = 0$
- $W^j_p = 0$ if $RQ_p = LQ_p = 0$
To determine partial picking tour up to pick aisle \( p \) given it is exited at cross aisle \( j \), calculate:

\[
f_p(j) = \min_{i_p = p-1} \left\{ X_p(i, j) + f_{p-1}(j) \right\}
\]  

(4-2)

As \( i_p = j_{p-1} \), every \( X_p(i, j) \) given an \( i \) corresponds to one \( f_{p-1}(j) \). Evaluate \( f_p(j) \) up to pick aisle \( z \).

- Step 3: After all the items are picked and the picker has exited to the front of the warehouse, return to starting point. The length of this path can be calculated using equation (2-10).

Construct full picking tour as \( G_d + f_z(i) + G_z \).

### 4.2.5 Tour Construction and Length Calculation

Using the above model, picking tour length is calculated for every order list issued in April 2013. This is to find out the performance of the current order sequencing/sorting method and find tour length for every order list. Here, a demonstration of tour construction and tour length calculation are provided. This is done to give a thorough explanation and look on the tour construction, shape, and length given an actual order picking problem.

The order list used in this demonstration of tour construction and length calculation is order list no. 382565. Order list no. 382565 itself contains 22 orders located in 22 pick locations. The pick locations are C3, C6, C12, C14, C22, C24, C30, C32, D24, D26, D33, E9, E24, E26, E32, E58, I24, I35, I41, I49, I54, and J57. The following diagram is the resulting order picking problem/scheme of order list 382565 in CEVA XNZ warehouse. The pick locations are highlighted in orange. Picking starts from the red circle on the right bottom corner, next to depot where the order list is issued.
<table>
<thead>
<tr>
<th>N</th>
<th>M</th>
<th>L</th>
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<th>J</th>
<th>H</th>
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Figure 4.9 Order picking problem of order list 382565
The first pick aisle containing at least one pick aisle ($d$) is pick aisle 2, and the last ($z$) is pick aisle 6. Starting from depot (red circle), the picker travels to the front cross aisle of pick aisle. The length of this path is

$$G_d = (d - 1) \times 4 = (2 - 1) \times 4 = 4 \text{ m}$$

From this point the construction of partial picking tour starts. $X_p(i,j)$ are constructed and $f_p(j)$ are evaluated for pick aisle 2 to 6:

- Pick aisle 2 has racking column B and C to pick from, containing 0 and 6 pick locations, respectively. The distance $V_p^3$ from entrance to C3 is 60 m. $RQ_2 = 0$, thus $RC_2 = 0$ and $BT_2 = 0$. The length $LC_2$ from C3 to C32 is 29 m. Since pick aisle 2 is pick aisle $d$, $T = 0$. From C32 there are 3 cross aisles to move to:
  - Cross aisle 1, with the distance $W_2^1$ of 33 m.
  - Cross aisle 2, with the distance $W_2^2$ of 2 m.
  - Cross aisle 3, with the distance $W_2^3$ of 31 m.

Pick aisle is entered from front cross aisle (cross aisle 3). This results in 3 possible $X_2(3,j)$ for every $j$:

- $X_2(3,1) = V_2^3 + LC_2 + W_2^1 = 60 + 29 + 33 = 122 \text{ m}$
- $X_2(3,2) = V_2^3 + LC_2 + W_2^2 = 60 + 29 + 2 = 91 \text{ m}$
- $X_2(3,3) = V_2^3 + LC_2 + W_2^3 = 60 + 29 + 31 = 120 \text{ m}$

Evaluation of $f_p(j)$ for pick aisle 2 produces the result $f_2(j) = X_2(3,j)$ since this pick aisle is entered from the front of the warehouse and there are no preceding partial tours.

- Pick aisle 3 has racking D and E to pick from, containing 3 and 5 pick locations, respectively. Length of $T = 4$, $RC_3 = 12 \text{ m}$, $BT_3 = 27 \text{ m}$, and $LC_3 = 52 \text{ m}$. The values of $W_3^1$, $W_3^2$, and $W_3^3$ are 62 m, 27 m, and 2 m,
respectively. From this point, calculation is divided based on the possible number of cross aisle $i$:

- For $i = 1, V_3^1 = 25 \, \text{m}$. There are 3 possible $X_3(1,j)$:
  - $X_3(1,1) = T + V_3^1 + RC_3 + BT_3 + LC_3 + W_3^1 = 4 + 25 + 12 + 27 + 52 + 62 = 182 \, \text{m}$
  - $X_3(1,2) = T + V_3^1 + RC_3 + BT_3 + LC_3 + W_3^2 = 4 + 25 + 12 + 27 + 52 + 27 = 147 \, \text{m}$
  - $X_3(1,3) = T + V_3^1 + RC_3 + BT_3 + LC_3 + W_3^3 = 4 + 25 + 12 + 27 + 52 + 2 = 122 \, \text{m}$

- For $i = 2, V_3^2 = 10$. There are 3 possible $X_3(2,j)$:
  - $X_3(2,1) = T + V_3^2 + RC_3 + BT_3 + LC_3 + W_3^1 = 4 + 10 + 12 + 27 + 52 + 62 = 167 \, \text{m}$
  - $X_3(2,2) = T + V_3^2 + RC_3 + BT_3 + LC_3 + W_3^2 = 4 + 10 + 12 + 27 + 52 + 27 = 132 \, \text{m}$
  - $X_3(2,3) = T + V_3^2 + RC_3 + BT_3 + LC_3 + W_3^3 = 4 + 10 + 12 + 27 + 52 + 2 = 107 \, \text{m}$

- For $i = 3, V_3^3 = 39$. There are 3 possible $X_3(3,j)$:
  - $X_3(3,1) = T + V_3^3 + RC_3 + BT_3 + LC_3 + W_3^1 = 4 + 39 + 12 + 27 + 52 + 62 = 196 \, \text{m}$
  - $X_3(3,2) = T + V_3^3 + RC_3 + BT_3 + LC_3 + W_3^2 = 4 + 39 + 12 + 27 + 52 + 27 = 161 \, \text{m}$
  - $X_3(3,3) = T + V_3^3 + RC_3 + BT_3 + LC_3 + W_3^3 = 4 + 39 + 12 + 27 + 52 + 2 = 136 \, \text{m}$

The results of evaluating $f_3(j)$ using equation (4-2) are:

- $f_3(1) = \min_{i_p=j_{p-1}}\{X_3(i, 1) + f_2(j)\} = X_3(2,1) + f_2(2) = 167 + 91 = 258 \, \text{m}$
- $f_3(2) = \min_{i_p=j_{p-1}}\{X_3(i, 2) + f_2(j)\} = X_3(2,2) + f_2(2) = 132 + 91 = 223 \, \text{m}$
- $f_3(3) = \min_{i_p=j_{p-1}}\{X_3(i, 3) + f_2(j)\} = X_3(2,3) + f_2(2) = 107 + 91 = 198 \, \text{m}$
• Pick aisle 4 has racking F and G to pick from, but both do not contain any pick locations. In this case, the pick aisle is skipped, exited immediately after it is entered from the same cross aisle \((i = j)\), and the value of \(X_4(i, j) = T = 4\). Evaluation of \(f_4(j)\) yields:
  - \(f_4(1) = X_4(1,1) + f_3(1) = 4 + 258 = 262 \text{ m}\)
  - \(f_4(2) = X_4(2,2) + f_3(2) = 4 + 223 = 227 \text{ m}\)
  - \(f_4(3) = X_4(3,3) + f_3(3) = 4 + 198 = 202 \text{ m}\)

• Pick aisle 5 has racking H and I to pick from, containing 0 and 5 pick locations, respectively. Since \(R_Q = 0\), the values of \(RC_5\) and \(BT_5\) are 0. The length \(LC_5 = 33 \text{ m}\) from I24 to I54. The values of \(W_5^1, W_5^2,\) and \(W_5^3\) are 58 m, 23 m, and 6 m, respectively. Evaluate \(X_5(i, j)\) for every \(i\) and \(j\) combination:
  - For \(i = 1, V_5^1 = 25 \text{ m}\). There are 3 possible \(X_5(1, j)\):
    - \(X_5(1,1) = T + V_5^1 + LC_5 + W_5^1 = 4 + 25 + 33 + 58 = 120 \text{ m}\)
    - \(X_5(1,2) = T + V_5^1 + LC_5 + W_5^2 = 4 + 25 + 33 + 23 = 85 \text{ m}\)
    - \(X_5(1,3) = T + V_5^1 + LC_5 + W_5^2 = 4 + 25 + 33 + 6 = 68 \text{ m}\)
  - For \(i = 2, V_5^2 = 10 \text{ m}\). There are 3 possible \(X_5(2, j)\):
    - \(X_5(2,1) = T + V_5^2 + LC_5 + W_5^1 = 4 + 10 + 33 + 58 = 105 \text{ m}\)
    - \(X_5(2,2) = T + V_5^2 + LC_5 + W_5^2 = 4 + 10 + 33 + 23 = 70 \text{ m}\)
    - \(X_5(2,3) = T + V_5^2 + LC_5 + W_5^2 = 4 + 10 + 33 + 6 = 53 \text{ m}\)
  - For \(i = 3, V_5^3 = 39 \text{ m}\). There are 3 possible \(X_5(3, j)\):
    - \(X_5(3,1) = T + V_5^3 + LC_5 + W_5^1 = 4 + 39 + 33 + 58 = 134 \text{ m}\)
• $X_5(3,2) = T + V_5^3 + LC_5 + W_5^2 + 4 + 39 + 33 + 23 = 99 \text{ m}$
• $X_5(3,3) = T + V_5^3 + LC_5 + W_5^3 = 4 + 39 + 33 + 6 = 82 \text{ m}$

The results of evaluating $f_5(j)$ are:
  
  o $f_5(1) = \min_{i_p = j_{p-1}} \{X_5(i, 1) + f_4(j)\} = X_5(2,1) + f_4(2) = 105 + 227 = 332 \text{ m}$
  o $f_5(2) = \min_{i_p = j_{p-1}} \{X_5(i, 2) + f_4(j)\} = X_5(2,2) + f_4(2) = 70 + 227 = 297 \text{ m}$
  o $f_5(3) = \min_{i_p = j_{p-1}} \{X_5(i, 3) + f_4(j)\} = X_5(2,3) + f_4(2) = 53 + 227 = 297 \text{ m}$

• Pick aisle 6 has racking J and K to pick from, and contains only one pick location, J57. $RQ_6 = 1$ and $LQ_6 = 0$, making the values of $RC_6$, $BT_6$, and $LC_6$ equal to 0. Since this is the last pick aisle, it has to be exited at the front of the warehouse (cross aisle 3), with $W_6^3 = 3 \text{ m}$. Evaluating $X_6(i, 3)$ for every $i$ yields:
  
  o For $i = 1$, $V_6^1 = 61 \text{ m}$, and $X_6(1,3) = T + V_6^1 + W_6^3 = 4 + 61 + 3 = 68 \text{ m}$
  o For $i = 2$, $V_6^2 = 26 \text{ m}$, and $X_6(2,3) = T + V_6^2 + W_6^3 = 4 + 26 + 3 = 33 \text{ m}$
  o For $i = 3$, $V_6^3 = 3 \text{ m}$, and $X_6(3,3) = T + V_6^3 + W_6^3 = 4 + 3 + 3 = 10 \text{ m}$

Evaluating $f_6(3)$ yields the resulting partial picking tour length:

$$f_6(3) = \min_{i_p = j_{p-1}} \{X_6(i, 3) + f_5(j)\} = X_6(3,3) + f_5(3) = 10 + 280 = 290 \text{ m}$$
The resulting tour is $f_6(3) = X_2(3,2) + X_3(2,2) + X_4(2,2) + X_5(2,3) + X_6(3,3)$

From the front cross aisle of pick aisle 6, the picker walks back to depot. The length of this tour is

$$G_6 = G_6 = (6 - 1) \times 4 = 20 \text{ m}$$

After reaching depot, the full picking tour length can be calculated. The full picking tour length is

$$G_2 + f_6(3) + G_6 = 4 + 290 + 20 = 314 \text{ m}$$

The following diagram illustrates the resulting full picking tour. The blue dots mark the points in the tour where the picker picks from the right column and the yellow dots mark where the picker picks from the left. The resulting tour length by current method for every order list can be seen in Appendix 2 under the column “Current”.
Figure 4.10 Full picking tour of order list 382565 using current method
4.3 Proposed Method Model Construction and Tour Length Calculation

4.3.1 Warehouse Sectioning and Numbering

The following diagram depicts the warehouse sectioning and numbering required for picking tour construction with C-combined heuristic.

For C-combined heuristic, this warehouse layout is divided into top block (block 1) and the bottom block (block 2), separated in the middle by the middle cross aisle. The cross aisles are not numbered, but rather identified as back and front aisle cross aisle for each block. The cross aisle in the middle is front cross aisle for
the top block and back cross aisle for bottom block. Pick aisles are separated in the middle and each halves become subaisles in their respective block. The subaisles are numbered from right to left and in-line subaisles are numbered the same.

4.3.2 Routing Definition

C-combined heuristic is a modification on combined heuristic by Roodbergen and de Koster (2001). As with other block heuristics, C-combined heuristic follows the same scheme of picking order: from the farthest block to the nearest. Consider an order picking problem $X$ from Section 4.2.2. The pick locations are spread in the two blocks, top and bottom. Picking starts from the right bottom of the warehouse. The picker travels to the front of the farthest block containing pick locations, in this case the top block. If pick locations are located only in the bottom block, this movement is not necessary. Figure 4.12 illustrates this movement for order picking problem $X$. The red circle and blue circle marks where the movement starts and ends, respectively.

Figure 4.12 Picker movement from depot to front cross aisle of top block
The length of pick aisle within one block is identified as subaisle. From the right bottom corner of this block the picker identifies the first subaisle containing picks and go to the front of it, as depicted in figure 4.13.

![Figure 4.13 Picker movement to first subaisle with at least one pick location in the top block](image)

From this point the block picking starts. Using dynamic programming, the shortest partial picking tour from the first to the last subaisle containing at least one pick location. A subaisle can either be exited from the top or bottom cross aisle after all items are picked. Since at this point the picker is at the front cross aisle, the possible routes are: traversing the subaisle entirely and exiting from the back cross aisle (1), or walking to the farthest pick location and going back to exit from the front cross aisle (2). The illustration for this can be seen in figure 4.14. Note that the horizontal lines represent turns the picker makes and do not add length to the picking tour.

Since there are 2 ways to exit the first subaisle and also two ways to exit the next, that creates 4 possible tours, depicted in figure 4.15:

- The first subaisle is exited from the front and the second subaisle is exited from the front (a).
- The first subaisle is exited from the front and the second subaisle is exited from the back (b).
- The first subaisle is exited from the back and the second subaisle is exited from the front (c).
- The first subaisle is exited from the back and the second subaisle is exited from the back (d).
Dynamic programming function is then used to determine the minimum partial tour that ends on both front and back cross aisle. The length of partial tour up to a given subaisle equals to the length of (1) or (2) in that pick aisle plus the length of partial tour up to the previous pick aisle. Note that if that particular pick aisle does not contain any items, the picker “skips” it and move to the next subaisle. Applying dynamic programming to the cases in figure 4.15 produces the result of (c) and either (b) or (d) (both share the same length) for minimum partial picking tours that ends in the front and back cross aisle, respectively. Since the block
picking has to end in front cross aisle, dynamic programming result for partial
picking tour that ends on the back cross aisle in the last subaisle is not considered.
The resulting partial picking tour for the top block is illustrated in figure 4.16.

![Figure 4.16 Final top block partial picking tour of order picking problem X](image)

After all the items in top block are picked, the picker moves on to pick from the
bottom block. By now the picker is located in the front cross aisle of the top block
which is also the back cross aisle of the bottom block, so the next step is to move
to the back cross aisle of the first subaisle containing at least one pick location.

This is where this heuristic differs from combined heuristic explained in chapter 2.
With combined heuristic, the picker has to determine that first subaisle by
choosing which of the farthest subaisles from his position, rightmost or leftmost
subaisle with at least one pick, is closer to him/her. If the closer one is former the
picker starts from there and the block picking is done from left to right and vice
versa. The problem with this is that if the block picking ends in the leftmost
subaisle, the picker has to travel the length of the horizontal distance he/she
already covered during block picking plus the horizontal distance between the first
subaisle in that block to the depot, which is not the case if the block picking starts
from leftmost subaisle.

This heuristic, however, arbitrarily determine that picking from the last block
starts from the leftmost subaisle containing at least one pick location. That way no
horizontal length is covered twice and the resulting full picking tour will be at
worst the same length than if the same order picking problem is solved with combined heuristic. This arbitrary block entering rule is one of the two improvements of combined heuristic from combined heuristic.

![Figure 4.17 Transition from top block’s last subaisle to bottom block’s first subaisle of order picking problem X](image1.png)

The construction of partial picking tour in this block is almost the same as the top block, with the only differences being the picking starts at the back cross aisle of the block and is done from left to right.

![Figure 4.18 Final bottom block partial picking tour of order picking problem X](image2.png)

After the bottom block picking ends, the picker traverses the front cross aisle to reach depot. The full picking tour is illustrated in figure 4.19, with the red circle representing the starting and ending point and the yellow dots marking the points in the tour where the picker retrieves items from the pick locations.
4.3.3 Notation of Elements
The method of constructing partial picking route within a block is the same between C-combined and combined heuristic. Therefore the notation for all the elements involved in it can be referred from chapter 2 section 2.4.1.3

However, the explanation on combined heuristic on chapter 2 section 2.4.1.3 only covers about partial picking tour construction in a block. Therefore, several elements are identified to complete the notation list:

- $M_i$: Vertical distance to front cross aisle of block $i$.
- $N_i$: Horizontal distance to reach subaisle $l$ (first subaisle to pick from) in block $i$.
- $Y$: Horizontal distance from the last subaisle containing in the warehouse containing at least one pick location to depot.

4.3.4 C-combined Heuristic Routing Model
This model creates full picking tour for this warehouse layout. The length of picking tour is the sum of total length of partial picking tour of the two blocks.
plus distance to move to/from and between blocks. The steps of constructing partial picking tour (block picking) is covered in chapter 2 section 2.4.1.3, so this model contains additional detail to complete the full picking tour. The steps are:

- Step 1: The picker travels from depot to the front of the farthest block containing at least one pick location \( (M_i) \). Since there are 2 blocks in this warehouse there are 2 possibilities:
  - If \( i = 1 \), the picker traverses the aisle from depot to block 1, with length of \( M_1 = 29 \) m.
  - If \( i = 2 \), the picker skips this movement \( (M_2) \) and go directly to step 2.

- Step 2: Picker travels the length \( N_i \) to reach the subaisle \( l \) in block \( i \). The travel length is \( (l - 1) \times 4 \) m

- Step 3: From this point, partial picking tour in this block \( i \) is constructed. Refer to equation (2-2), (2-3), (2-4), (2-5), and (2-6) to do this. Picker retrieves all items in block \( i \) and exits at the front cross aisle.
  - If \( i = 1 \), go to step 4
  - If \( i = 2 \), go to step 6

- Step 4: Determine if the next block (block 2) contains pick locations.
  - If block 2 contains pick locations, make the transition \( N_i \) (remember that from here picking starts at the leftmost subaisle containing at least one pick location) and go to step 5.
  - If there are none in block 2, traverse the nearest subaisle to the front of the warehouse \( (M_2 = 29 \) m) and go to step 6.

- Step 5: Create partial picking tour for this block that finishes in the front of the warehouse.

- Step 6: From this point, return to depot \( (Y) \). The length of this movement is \( (r - 1) \times 1 \) (with \( r \) being the last subaisle of the last subaisle containing as least one pick location).
4.3.5 Tour Construction and Length Calculation

Same with the current method, C-combined heuristic is used to full picking tour for every order list of April 2013. The difference is between C-combined heuristic with the current method is that with the current sequencing method the picking tour is resulted from the order picking sequencing/sorting, while using C-combined heuristic the order sequence are determined after the full picking tour given an order list is constructed. Also using order list 382565, a demonstration of picking tour construction and tour length calculation are conducted to see how C-combined performs. Refer to section 4.2.5 to see the contents of order list 382565. The resulting order picking sequence is presented after the full picking tour construction and resulting full tour length calculation. Additionally, refer to figure 4.9 to see the illustration of the resulting order picking problem of order list 382565.

Dividing the warehouse into two blocks (as it is required when using C-combined heuristic in this particular warehouse layout), it is found that both top and bottom blocks contain picks. From depot, the picker travels to the front cross aisle of block 1 through subaisle 1 ($M_1 = 29 m$). The first subaisle in block 1 containing at least one pick location is subaisle 2, and the last one is subaisle 5. From the bottom right corner of block 1, the picker traverses its front cross aisle to the front subaisle 2. The length of this movement is

\[ N_1 = (2 - 1) \times 4 = 4 \text{ m} \]

From here partial picking tour for block 1 starts:

- Subaisle 2 contains 8 pick locations, the highest being pick location. C3. The distance from starting point to C3 is 31 m. The distance between the front and back cross aisle is 35 m. Here 2 possible routes $L_2^a$ and $L_2^b$ are evaluated. The route starts from the front cross aisle ($b$). The length of each route is:
  - $L_2^a = t_1 = 35 \text{ m}$
  - $L_2^b = t_3 = 2 \times 31 = 62 \text{ m}$
Subaisle 3 contains 6 pick locations, the highest one is E9 and the lowest one is E32. The distance from front cross aisle to E9 is 25 m. The distance from back cross aisle to E32 is 33 m. The distance between adjacent subaisle is 4 m. Evaluating $L_3^a$ and $L_3^b$ yields:

- $L_3^a = \min \left( \frac{L_2^a + t_a + t_4}{L_2^b + t_b + t_1} \right) = \min \left\{ \frac{35 + 4 + (2 \times 33)}{62 + 4 + 35} \right\} = 62 + 4 + 35 = 101 \text{ m}$
- $L_3^b = \min \left( \frac{L_2^a + t_a + t_4}{L_2^b + t_b + t_3} \right) = \min \left\{ \frac{35 + 4 + 35}{62 + 4 + (2 \times 25)} \right\} = 35 + 4 + 74 \text{ m}$

Subaisle 4 contains no pick locations, therefore it is skipped. The partial tour lengths up to this point are:

- $L_4^a = L_3^a + t_a = 101 + 4 = 105 \text{ m}$
- $L_4^b = L_3^b + t_b = 74 + 4 = 78 \text{ m}$

Subaisle 5 contains 1 pick location, I24. The distance to I24 from front cross aisle is 10 m. Since subaisle 5 is the last subaisle with at least one pick location in block 1, only $L_5^b$ is evaluated. The evaluation yields:

$$L_5^b = \min \left\{ \frac{L_4^a + t_a + t_1}{L_4^a + t_b + t_3} \right\} = \min \left\{ \frac{105 + 4 + 35}{78 + 4 + (2 \times 10)} \right\} = 78 + 4 + (2 \times 10) = 102 \text{ m}$$

The resulting tour is $L_5^b = t_1 + t_a + t_1 + t_b + t_b + t_3$. The following diagram illustrates partial picking tour in this block. The red circle represents the starting point, the blue circle represents the end point, and the yellow dots mark the points in the tour where the picker retrieves items from the pick locations.
Figure 4.20 Block 1 partial picking tour of order list 382565

Picking tour ends in front of subaisle 5 of block 1. The next step is to complete picking in block 2. The leftmost subaisle containing at least one pick in block 2 is subaisle 6, and the rightmost is subaisle 3. The picker travels to back of subaisle 6 with the length movement length of

\[ N_2 = (6 - 5) \times 4 = 4 \text{ m} \]

to start picking tour in block 2.

- Subaisle 6 contains 1 pick location, J57. The distance from starting point to J57 is 26 m. The distance between the front and back cross aisle is 29
Here 2 possible routes $L^a_6$ and $L^b_6$ are evaluated. The route starts from the back cross aisle ($a$). The length of each route is:

- $L^a_6 = t_4 = (2 \times 26) = 52$ m
- $L^b_6 = t_1 = 29$ m

- Subaisle 5 contains 4 pick locations, the highest one is I35 and the lowest one is I54. The distance from front cross aisle to I35 is 25 m. The distance from back cross aisle to I54 is 23 m. Evaluating $L^a_5$ and $L^b_5$ yields:
  - $L^a_5 = \min \left\{ L^a_6 + t_a + t_4 \right\} = \min \left\{ 52 + 4 + (2 \times 23) \right\} = 29 + 4 + 29 = 62$ m
  - $L^b_5 = \min \left\{ L^b_6 + t_b + t_1 \right\} = \min \left\{ 29 + 4 + (2 \times 25) \right\} = 83$ m

- Subaisle 4 contains no pick locations, therefore it is skipped. The partial tour lengths up to this point are:
  - $L^a_4 = L^a_5 + t_a = 62 + 4 = 66$ m
  - $L^b_4 = L^b_5 + t_b = 83 + 4 = 87$ m

- Subaisle 3 contains 2 pick location, E33 and E58. The distance to E33 from front cross aisle is 27 m. Since subaisle 3 is the last subaisle with at least one pick location in block 2, only $L^b_3$ is evaluated. The evaluation yields:

$$ L^b_3 = \min \left\{ \frac{L^a_4 + t_a + t_1}{L^b_4 + t_b + t_3} \right\} = \min \left\{ \frac{66 + 4 + 29}{87 + 4 + (2 \times 27)} \right\} = 66 + 4 + 29 = 99$ m

The resulting tour is $L^b_3 = t_1 + t_b + t_1 + t_a + t_a + t_1$. The following diagram illustrates partial picking tour in this block.
From the front of subaisle 3, the picker walks back to depot. The length of this movement is $Y = (3 - 1) \times 4 = 8 \text{ m}$. This move concludes the full picking tour of order picking problem 382565 with C-combined heuristic. Total length of this picking tour is $M_1 + N_1 + L_5^b + N_2 + L_3^b + Y = 29 + 4 + 102 + 4 + 99 + 8 = 246 \text{ m}$. Diagram below illustrates the full picking tour.
Figure 4.22 Full picking tour of order list 382565 using C-combined heuristic
The resulting tour length by C-combined heuristic for every order list can be seen in Appendix 2 under the column “C-combined”. From the resulting full picking tour in figure 4.22, Order picking sequence can be determined by following the order of which the route visits the pick locations (marked by yellow dots). The order picking sequence of order list 382565 with C-combined heuristic is: C32, C30, C24, C22, C14, C12, C6, C3, E9, D24, E24, D26, E26, E32, I24, J57, I54, I49, I41, I35, D33, and E58. D24 and E24 are located in front each other, and so are D26 and E26. The order of these pairings can be interchanged within an order picking sequence without affecting the tour length. This is because each pairing is visited at the same point in the picking tour.

4.4 Comparison and Analysis

4.4.1 Comparing the Performance of Current and C-combined Heuristic

When constructed using the current sequencing method, the full picking tour of order list 382565 measures 314 m. On the other hand, full picking tour of order 382565 constructed using C-combined heuristic is 246 m long. The C-combined heuristic generated tour is 68 m shorter than the one generated by current method for this order list. The improvement/reduction in length is

\[
\frac{(314 - 246)}{314} = \frac{68}{314} = 0.21656 = 21.656\% 
\]

C-combined has successfully produced a significantly shorter picking tour for order list 382565. The resulting tour lengths of both current and C-combined heuristic, along with reduction in length (%) if C-combined is utilized, for every order list are presented in Appendix 2. The following table is the layout of Appendix 2.

<table>
<thead>
<tr>
<th>Order List</th>
<th>Size</th>
<th>Length (m)</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Current</td>
<td>C-combined</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1 Comparison between current method and C-combined heuristic tour length (part of Appendix 2)
<table>
<thead>
<tr>
<th></th>
<th>382549</th>
<th>21</th>
<th>300</th>
<th>180</th>
<th>40.00%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>382553</td>
<td>45</td>
<td>408</td>
<td>276</td>
<td>32.35%</td>
</tr>
<tr>
<td></td>
<td>382557</td>
<td>23</td>
<td>252</td>
<td>176</td>
<td>30.16%</td>
</tr>
<tr>
<td></td>
<td>382562</td>
<td>24</td>
<td>490</td>
<td>342</td>
<td>30.20%</td>
</tr>
<tr>
<td></td>
<td>382565</td>
<td>22</td>
<td>314</td>
<td>246</td>
<td>21.66%</td>
</tr>
</tbody>
</table>

Drawing results from Appendix 2, it is found that the total tour length of all 573 order lists is 200149 m, or 200.149 km, if they are constructed using current method. The average picking tour length using the current method is

$$\frac{200149}{573} = 349.3 \text{ m}$$

On the other hand, the total tour length is 126820 m, or 126.82 km, if they are constructed using C-combined heuristic. The average picking tour length using C-combined heuristic is

$$\frac{126820}{573} = 221.326 \text{ m}$$

To compare the performance of current method and C-combined heuristic, the following charts are presented. The charts contain the comparison between total picking tour length and average picking tour length.
As can be seen from figure 4.23, C-combined heuristic performs better than the current method. It successfully produces significantly shorter total and average picking tour length compared to the current order sequencing/sorting method. The total and average picking tour length C-combined heuristic produces is 36.64% shorter compared to that of current heuristic. The reduction of tour length ranges from 0% (order list 389359), meaning no reduction at all, to 56.54% (order list 395720). The following is a part of Appendix 2 that shows these results.

Table 4.2 Tour length comparison for order list 389359 and 395720 (part of Appendix 2)

<table>
<thead>
<tr>
<th>Order List</th>
<th>Size</th>
<th>Length (m)</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Current</td>
<td>C-combined</td>
</tr>
<tr>
<td>389359</td>
<td>18</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>395720</td>
<td>104</td>
<td>994</td>
<td>432</td>
</tr>
</tbody>
</table>

There is, however, case in which C-combined produced longer tour length compared to the current method tour length. This happens to order list 384603. Order list 384603 consists of 21 orders located in 21 pick locations. The locations are: C6, C10, C12, C14, C16, C18, C22, C28, C32, E30, E50, G30, I24, I37, I45, I49, I54, I57, I58, J55, and J57. When the picking tour is constructed using the current method, the resulting tour length is 238 m. However, using the C-
combined heuristic, the resulting tour length becomes 248 m, 10 m longer than current method tour length. The increase in tour length when C-combined heuristic is applied is

\[
\frac{248 - 238}{238} = 0.042 = 4.2\%
\]

This is a unique occurrence given this set of order picking problem cases. Therefore, it is interesting to see the cause of this. Two figures are provided in the next two pages as visualizations of the picking tours. The first one, figure 4.24, illustrates the resulting full picking tour of 384603 using current method. The second one, figure 4.25, illustrates the resulting full picking tour of 384603 using C-combined heuristic. In both figures, picking starts and ends at the depot, represented by the red circle. For figure 4.24, the extraction points are marked with the blue dots if the pick location is in the right column and yellow dots if the pick location is in the left column, within a pick aisle. In figure 4.25, the extraction points are marked with yellow dots.
Figure 4.24 Full picking tour of order list 384603 using current method
Figure 4.25 Full picking tour of order list 384603 using C-combined heuristic
In figure 4.24 and 4.25, it can be seen that in order picking problem of order list 384603 the pick aisles and subaisles only contain pick locations one side rather than both sides. This means that the added aisle picking length usually associated with current order sequencing (refer to chapter 1 section 1.1) is non-existent. As both picking tour shares the same case, the horizontal length (from depot to the farthest aisle containing picks and back) of both picking tour are the same. This leaves the vertical length to be observed to find the difference in tour length.

To facilitate this observation, the warehouse is divided into top and bottom blocks for both cases. Observing the top block of both figure 4.24 and 4.25, it is found that the picking route in every subaisle has the same length and shape. Again, this is possible due to the way the pick locations are spread in this order picking problem. Therefore, the difference must lie in the bottom block.

Observing the bottom block, there are some differences in how the subaisles that contain picks are traversed. Subaisle 5 (between column H and I) are traversed entirely in both tours, though in different directions. However, subaisle 3 (between D and E) and subaisle 6 (between column J and K) are traversed differently in both tours. In current method’s picking tour, subaisle 3 is entered from and exited at front cross aisle while subaisle 6 is entered from and exited at the middle cross aisle. In C-combined heuristic’s picking tour, both subaisles are traversed entirely, from middle to front cross aisle. The length of picking tour in subaisle 3 and 6 of bottom block for current method’s picking tour is 38 m and 10 m respectively, while for C-combined’s picking tour is 29 m for both subaisles. As the rest of the lengths are the same between both tours, the difference in length between the two tours is

\[(2 \times 29) - (38 + 10) = 58 - 48 = 10 \, m\]

This result indicates that C-combined heuristic does not always perform better than the current method. Given a certain order picking problem configuration, current method may perform better.
The shape of picking tour using current order sequencing is similar to the shape of picking tour constructed with lateral heuristic. This may therefore raise the argument of using the aisle-by-aisle heuristic by Ertek et al. (2007) (see chapter 2 section 2.2.3). However, Roodbergen and de Koster (2001) compared the performance of aisle-by-aisle heuristic and combined heuristic. The comparison is done different combinations of warehouse settings and order list sizes. The following diagram shows the comparison.

<table>
<thead>
<tr>
<th>Method</th>
<th>No. of aisles</th>
<th>Length</th>
<th>No. of items</th>
<th>Number of cross aisles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Aisle-by-aisle</td>
<td>7</td>
<td>10</td>
<td>10</td>
<td>148.5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>30</td>
<td>10</td>
<td>144.3</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>10</td>
<td>30</td>
<td>153.7</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>10</td>
<td>30</td>
<td>164.6</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>10</td>
<td>30</td>
<td>177.5</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>10</td>
<td>30</td>
<td>189.9</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>10</td>
<td>30</td>
<td>205.4</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>10</td>
<td>30</td>
<td>216.4</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>10</td>
<td>30</td>
<td>230.3</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>10</td>
<td>30</td>
<td>245.6</td>
</tr>
</tbody>
</table>

(Source: Roodbergen and de Koster, 2001)

Figure 4.26 Comparison between aisle-by-aisle and combined heuristic

Each situation is a combination of different number of aisles, warehouse length, number of items, and number of cross aisles. There are 2 number of aisles settings (7 and 15), 2 warehouse length settings (10 m and 30 m), 2 number of items settings (10 and 30), and 10 number of cross aisles settings (2-11), totaling in $2 \times 2 \times 10 = 80$ different situations. The values in each situation are the average travel time (in seconds) of each combination settings, resulting from 2000 replications. It can be seen from the above figure that if the warehouse has 2 cross aisles, aisle-by-aisle and combined heuristic performed the same on $2 \times 2 \times 2 = 8$ possible situations. However, on 3-cross-aisles setting, combined heuristic performs better on every of the 8 possible situations compared to aisle-by-aisle
heuristic. Under this consideration, the author chose to modify combined heuristic to improve order picking activity in CEVA XNZ warehouse.

While C-combined performed worse in one case compared to the current method and same as it in one other, it improves the order picking sequencing in the rest of the cases. On average, C-combined improves the generated picking tour by 36.04%. This shows that this kind of shortcoming very rarely occurs given the low probability of cases similar to order list 384603 coming up. With the significant improvement C-combined capable of making, as demonstrated on 573 order lists of April 2013, the author proposes for C-combined heuristic to be applied in CEVA XNZ warehouse.

4.4.2 Implementing C-combined Heuristic in CEVA XNZ Warehouse
C-combined heuristic is proven successful in improving order picking sequencing in CEVA XNZ warehouse. However, for practical application these heuristics have to be translated in a way that the practitioners, in this case the pickers, can carry out the necessary actions to produce the intended result. According to Bartholdi and Hackman (2011), giving only order sequences and not the instruction to reach them can make construction of the intended tour unlikely as it is not easy for picker to visualize the route. On brief observation, the resulting order sequence generated by C-combined might not make sense to a picker.

That is why the current heuristic works: the picker only has to follow the order of which the items are located. The decision making involved (such as which cross aisle to go through to reach the next pick location) is minimal and easy to process, making the tour pattern clear and easy to follow. The following table depicts the order list layout currently used in CEVA XNZ based on order list 382565. The information of SKU code, name and quantity is not provided as they are trivial to the picking tour construction process.
Table 4.3 Order list 382565 using current layout

<table>
<thead>
<tr>
<th>Slot</th>
<th>SKU Code</th>
<th>SKU Name</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>C6</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>C12</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>C14</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>C22</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>C24</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>C30</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>C32</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>D24</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>D26</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>D33</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>E9</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>E24</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>E26</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>E32</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>E58</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>I24</td>
<td>YYYYYY</td>
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<td>#</td>
</tr>
<tr>
<td>I35</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>I41</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>I49</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>I54</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
<tr>
<td>J57</td>
<td>YYYYYY</td>
<td>---------</td>
<td>#</td>
</tr>
</tbody>
</table>

This order list scheme only gives information on order list number (on the top right), pick slot code, SKU/item code, SKU name, and item quantity. While these information are sufficient for current routing method, they are not enough if the order list is to be sequenced based on C-combined heuristic because then the picker would have to decide which way to go him/herself. This added thinking and decision making process can make prolong the order picking process and make it too complicated to carry out. In addition to pick locations, the picker has
to be informed about what kind of route to take to get there. It is necessary, therefore, to eliminate the complicated and unnecessary decision making process involved in this. The following figure is an example of an order list/pick list that includes movement instruction for the picker to take.

![Figure 4.27 Example of an order list that includes travel directions](https://example.com/f4_27.png)

Another problem in applying C-combined heuristic order picking sequencing in CEVA XNZ is the current lack of detailed location concept in the warehouse. The pickers only recognize pick locations as “slots” due to lack of terming for aisles and the way the order is sequenced. Also, the current order picking sequence is dictated by the way each order list are sorted. Added processes are required to sequence the orders as in accordance to C-combined heuristic. Therefore, the author identifies 3 measures to implement C-combined heuristic in CEVA XNZ warehouse:

- Incorporation of a new type of information in the order lists (movement instruction).
- Introduction of several location concepts necessary for the pickers to understand the new order list layout.
- Integration of C-combined order sequencing process before order list generation.

To incorporate the new information, first it is necessary to determine the order of which the picker needs to process them. In the current layout, there are 4 types of information provided:

- Order list number (under the name “Order List No.”)
• Pick slot code (under the column “Slot”)
• SKU code (under the column “SKU Code”)
• SKU name (under the column “SKU Name”)
• SKU quantity (under the name “Quantity”)

In CEVA XNZ warehouse the items are identified as SKUs for operational convenience. The order list number is included for administrative reasons and is trivial in the picking process, thus the only important ones are the latter three. The procedure of picking given a line of order is as follows:

1) The picker identifies the pick location and travels to it.
2) The picker identifies the SKU code of the items located in that slot.
3) The picker identifies the SKU name, and then matches both the code and the name with the one in the order list.
4) If the SKU and the slot match the order list, the picker extracts a quantity of that SKU that is consistent with the number on the order list.

The leftmost information is pick location code, followed by SKU code, name, and quantity to its right. Assuming the order list is read left to right, this layout is accurate in providing right sequence of information.

After the picking process done with one order, the picker identifies the next pick slot that has to be visited. As the picker runs out of information to learn in that order line, he/she then turns to the next line. Again, given a C-combined sequenced order list, the picker might get confused with the next information provided. Therefore, it is ideal to put movement instruction before the picker identifies the next pick slot. Directing the picker to a neutral location (for example, in a cross aisle) is necessary for the picker to help processing what path he/she must take to get to the next location. Moreover, by clear instructions, the decision consideration is minimized. Thus the new layout will have an instruction included to the right of the column “Quantity” under the name “To Next Slot”. The following table illustrates the new order list layout proposed.
Table 4.4 Proposed order list layout

<table>
<thead>
<tr>
<th>Slot</th>
<th>SKU Code</th>
<th>SKU Name</th>
<th>Quantity</th>
<th>To Next Slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAA</td>
<td>YYYYYY</td>
<td>--------------</td>
<td>#</td>
<td>MMMMM</td>
</tr>
<tr>
<td>AAA</td>
<td>YYYYYY</td>
<td>--------------</td>
<td>#</td>
<td>MMMMMM</td>
</tr>
<tr>
<td>AAA</td>
<td>YYYYYY</td>
<td>--------------</td>
<td>#</td>
<td>MMMMMM</td>
</tr>
</tbody>
</table>

The introduction of “cross aisle” and “subaisle” concept is also necessary for the pickers in CEVA XNZ. The most important concept to introduce here is cross aisle, since the construction of partial block picking tour depends on the decision of which cross aisle to go through to get to the next subaisle/exit. The concept of “block” can be introduced to ease the pickers into understanding about subaisles (part of a pick aisle in a certain block). The concept of subaisle is introduced to give the pickers the positional sense required to understand the instructions (e.g.:”exit this subaisle to cross aisle …”). Technically, C-combined heuristic picking tour can be carried out without numbering the subaisles, cross aisles, and blocks. As long as the racking are numbered, the tour construction is still possible. To integrate C-combined heuristic in the order list generation process in CEVA, an added logic/processing has to be inserted before the order lists are printed and issued. The procedure of order list generation is as follows:

1) Orders are received in bulk from XNZ team by CEVA XNZ server
2) The IT department utilized the system to batch the orders into smaller groups
3) The system identifies the location of the ordered SKUs in the racking
4) The batched orders are sorted by location
5) The batched orders are printed and issued as order lists

The framework of this procedure is presented in figure 4.28.
As previously states in section 4.3.5, order picking sequencing for C-combined heuristic can only be determined after the full picking tour given an order list is constructed. By replacing the sorting process with a program that can simulate the full picking tour with C-combined heuristic, the order lists can then be sequenced properly. Using that program, first the locations of batched orders are determined and mapped on the warehouse layout. The program then constructs order picking tour using C-combined heuristic logic. Finally, it identifies the order of which the locations are visited, and then sequence the batches accordingly before being generated as order lists. The following figure illustrates the proposed framework for order list generation.
As a new order list layout is proposed, the result of order sequencing has to be generated with instructions to direct the picker. However, it is not necessary to give instructions after every pick. The author identifies several decision points in the picking tour. Decision points are points where the picker has more than one options of reaching the next intended location. Those points are:

- At the beginning of picking tour, to go to the first pick location
- At every last pick location in a subaisle, to go to the next one in the subsequent
- At the last pick location, to go back to depot

At the beginning of the picking tour, the picker has to determine the way to get to the first pick location. This is an easy task if pick locations are only located in the bottom block as logically the picker would only have one choice of path, which is to traverse along the front cross aisle and go up the subaisle that contains the first pick location. If the first pick location is in the top block and not in the first subaisle, the picker would then have to choose between 2 ways of getting there: going up the first subaisle, turning towards the middle cross aisle and up the subaisle containing the first pick location; or traversing the front cross aisle and up
the aisle that contains the pick location past the middle cross aisle. The C-combined heuristic model dictates that the picker must take the former route. But as resulting length of these routes is the same, taking either route would not affect the length of resulting tour. Figure 4.30 demonstrates this case.

![Figure 4.30 Two paths of the same length to get to first pick location in top block](image)

It is also possible to get there from the back cross aisle. However, it is easy to see that taking that route would result longer travel distance. This is because in taking this route, the picker would clearly have to make a turn around the racking. It is even easier if the first pick is located in the first subaisle of the top block, as the picker only has to go straight up from starting point. Therefore, an instruction for getting to the first pick location is not necessary.

A subaisle is exited after the last pick location in it is extracted from. There are 2 ways to exit a subaisle, from the way the picker came in or from the other end. This is done in every subaisle up to the last. In C-combined heuristic, the block picking tour construction is shaped by these decisions. It is vital then that the pickers always make the right decision to exit a subaisle. Therefore an instruction on how to exit a subaisle is given after every last pick location in it. The author identifies 2 types of instruction set for different blocks:

- In the first block, the 2 possible instructions are:
  - Exit to back cross aisle
  - Exit to middle cross aisle
In the second block, the 2 possible instructions are:

- Exit to middle cross aisle
- Exit to front cross aisle

The case of going back to the depot from the last pick location is pretty much the same as that of the first decision point. If the last pick location is in the block, the picker would be positioned at the front cross aisle (as per the order list instruction) and would only have to walk straight to depot. When it is in the top block however, there are 2 logical routes: through either middle or front cross aisle. Again, either route would result in the same length. Therefore, instructions are not given after the last pick location.

To conclude, instructions are only given after the last pick location in each subaisle containing picks. This policy should be ample enough to create a picking tour that is in accordance to C-combined heuristic. Though there might be variations, the length would be the same. The logic for giving instructions should be integrated with the order sequencing process. An example of the resulting order list built with this system is provided in table 4.4, based on order list 382565.

<table>
<thead>
<tr>
<th>Slot</th>
<th>SKU Code</th>
<th>SKU Name</th>
<th>Quantity</th>
<th>To Next Slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>C32</td>
<td>YYYYYY</td>
<td>-----------</td>
<td>#</td>
<td></td>
</tr>
<tr>
<td>C30</td>
<td>YYYYYY</td>
<td>-----------</td>
<td>#</td>
<td></td>
</tr>
<tr>
<td>C24</td>
<td>YYYYYY</td>
<td>-----------</td>
<td>#</td>
<td></td>
</tr>
<tr>
<td>C22</td>
<td>YYYYYY</td>
<td>-----------</td>
<td>#</td>
<td></td>
</tr>
<tr>
<td>C14</td>
<td>YYYYYY</td>
<td>-----------</td>
<td>#</td>
<td></td>
</tr>
<tr>
<td>C12</td>
<td>YYYYYY</td>
<td>-----------</td>
<td>#</td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>YYYYYY</td>
<td>-----------</td>
<td>#</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>YYYYYY</td>
<td>-----------</td>
<td>#</td>
<td>Exit to back cross aisle</td>
</tr>
<tr>
<td>E9</td>
<td>YYYYYY</td>
<td>-----------</td>
<td>#</td>
<td></td>
</tr>
</tbody>
</table>
This chapter has provided comparison of current and proposed method and the analysis of the result. Implementation/application suggestions have also been made here. This study’s conclusion and recommendations are presented in the next chapter.
CHAPTER V
CONCLUSION AND RECOMMENDATION

5.1 Conclusion
Summarizing the result of this study, some conclusions are made:

- The problem with the order sequencing method is that due to the way it creates longer picking tour given an aisle with two sides to pick from.
- C-combined heuristic performs at least as well as combined heuristic, and on average better than aisle-by-aisle heuristic given a warehouse with three cross aisles. This is concluded by drawing reference from Roodbergen and de Koster (2001)
- Using C-combined heuristic, the total and average tour length of order lists issued in April 2013 is improved by 36.64% compared to the ones of current method
- On average, C-combined heuristic improves the order picking tours by 36.04%
- Different from the current method, C-combined heuristic sequences the order list after the picking tour is determined.
- To apply C-combined heuristic CEVA XNZ must add the order list information content, integrate order sequencing processes in order list generation, and introduce the concept of cross aisle and subaisle to the pickers.

5.2 Recommendation
- This study is based on several assumptions. One of them is the assumption that the pickers have complete of knowledge of warehouse layout. If CEVA XNZ warehouse is to apply the proposed method in consideration of the author’s suggestions, they have to ensure that this assumption is realized. Even if they are not, thorough knowledge of warehouse racking is still necessary for operational excellence.
This study addresses the travel distance reduction issue using order picking sequencing method. However, looking at order lists 395714, 395716, and 395720 (size of 145, 141, and 104, respectively) which are significantly bigger in size compared to the rest of the order lists, the author suggests that future research to incorporate order batching problem, possibly using an integrated order batching and order sequencing method such as indexed batching method (IBM) by Hong et al. (2012) or hybrid algorithm by Chan and Cheng (2012).

This concludes the study “Application of Modified Combined Heuristic to Reduce Order Picking Tour Length in CEVA XNZ Warehouse”. The cited researches that support this study can be found in References section. Appendices section contains complete data collection and comparison of the methods’ performances.
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