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Original Article

A DATA-DRIVEN PICKING STRATEGY FOR MICRO FULFILMENT CENTERS IN QUICK COMMERCE: THE CASE OF KOREA

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Highlights:
- a hybrid picking strategy combining single order picking and batch picking is proposed for quick commerce micro fulfilment centers;
- the proposed strategy reduces the average picking time per order by 21.6% compared to the traditional single order picking system;
- the trade-offs between picking efficiency and delivery timeliness are analysed through simulation under a 30 min delivery window;
- the hybrid approach demonstrates its superiority by maintaining a high service level even as order density increases;
- the results provide practical operational guidelines for MFCs to balance picker productivity and strict delivery deadlines.

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Abstract. Quick Commerce (Q-Commerce) allows customers to receive their orders from near Micro Fulfilment Centers (MFCs) in a short time. However, the fulfilment centers are difficult to maintain responsive and reliable delivery services with traditional Single Order Picking (SOP) systems. Motivated by the above challenge, this study develops a hybrid picking method for an order fulfilment center of a Korean delivery company. The hybrid method considers certain rules for order batching to complement a SOP method. The order batching rules enable pickers to deal with 2 customer orders within a specific range of order lines. The order picking development are based on the results of a Warehouse Activity Profiling (WAP) analysis. This analysis shows possible approaches for the development of the hybrid method by considering arrival rates of customer orders and their variability in terms of item type and quantity. Afterwards, the hybrid method is validated with an agent-based simulation model using actual order information of the case study company. This study finds that the hybrid method shows consistent performance in terms of order picking and fulfilment times under wide ranges of order arrival rate and variability.

Keywords: online batch picking, single order picking, warehouse activity profiling, agent-based simulation, quick commerce.

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1. Introduction

The evolution of online shopping has caused a significant shift in customer purchasing behaviour. This behavioral transition has led to the emergence of Quick Commerce (Q-Commerce) with an increasing preference for on-demand fast delivery services. The Q-Commerce has a great potential to grow. It is expected to reach a global market size of 448 billion € by 2030 (Frazelle 2001). This prospect indicates that it has positioned itself as a new channel for customers to consume an array of products including foods and household items without time and place constraints.

Korea is the country where most customers can use internet to access online retail stores for purchasing. This market environment becomes the basis for development of the Q-Commerce in Korea (Ou 2025). In practice, there is an extensive delivery network of Micro Fulfilment Centers (MFCs) across urban areas. Most of the fulfilment centers are located in commercial buildings due to high property prices. For this reason, the fulfilment centers are often subject to small storage areas and narrow picking aisles, thereby they have no automation equipment available for order picking operations. Currently, each of the fulfilment centers has a Single Order picking System (SOP), i.e., a picking method where a picker retrieves items to fill a customer order in a single tour. This picking system has multiple pickers responsible for manually retrieving and packing items of customer orders in real-time manner. This implies that the fulfilment centers largely depends on picking performance of the pickers for successful order fulfilment.

The management of the manual order picking varies according to characteristics of customer orders. From an operational perspective, the Q-Commerce has 3 distinctive features in terms of order characteristics:

- 1st, it offers responsive delivery services that fulfil every order within a half of an hour. Therefore, a fast and reliable order picking method is required to observe such a tight order fulfilment timeline for the delivery services;
- 2nd, it allows for delivery of small numbers of items with no minimum purchase limit. Even a delivery of one single item is acceptable as customers are willing to bear a higher delivery cost. Thus, the picking method needs to be effective for orders with various order quantities and types of items;
- 3rd, it allows customers to place orders at any time they want. It means that the picking method also needs to have the capability to deal with the orders arriving at random during a day.

The above 3 features have posed a challenge for the development of an order picking method. As customers place orders for various types and quantities of items, pickers spend more time for item retrieval. Obviously, the longer picking time negatively affects order fulfilment performance of the fulfilment centers. To tackle this challenge, this study proposes a Hybrid Order Picking (HOP) method with variable order batch sizes. The hybrid method incorporates a batching picking method into the SOP system. The batching picking serves 2 different customer orders during a single picking tour by considering their numbers of order line. The development of the hybrid method uses a Warehouse Activity Profiling (WAP) analysis. This analysis presents a set of directions for the picking method development by considering actual order picking activities and customer order arrivals in an order fulfilment center of a Korean delivery company. Afterwards, this study performs numerical experiments to validate the hybrid picking method under various order picking environments. The results of the experiments show how and how much the hybrid method improves order picking performance in terms of waiting, picking and order fulfilment times.

The rest of the article is organized as follows:

- current Section 1 – an introduction;
- Section 2 reviews relevant literature on order picking method;
- Section 3 describes the current order picking activities and their performance in the case study company;
- Section 4 proposes the hybrid picking method from the results of the WAP analysis and carries out the numerical experiments;
- lastly, concluding remarks and future research directions are given in the Section 5.

2. Literature review

This section reviews literature to discuss the contributions of the current study. The contributions mainly come from the development of a new order picking method for order fulfilment centers in Q-Commerce. From an academic perspective, the new picking method is a variant of a picker-to-parts order picking, which has been studied in the context of warehousing decisions (e.g., item location, picker routing and order batching) and characteristics of customer orders (e.g., features of online and offline orders). Considering the scope of the current study, this section focuses on the literature on online order batching picking. Readers interested in other order picking methods are referred to Zhang *et al.* (2017), Chen *et al.* (2018), Cano *et al.* (2018), Cergibozan & Tasan (2019) and Hossein Nia Shavaki & Jolai (2021).

Order batching is a way of placing orders in batches to gain benefits from economies of scale. A successful order batching leads to greater productivity for order picking system with a large number of small orders (Gu *et al.* 2007; Chen *et al.* 2005, 2015; De Koster *et al.* 2007). In practice, the order batching handles various customer orders with different types and quantities of items. This order variability comes with a need for a new strategic approach for the order batching during the last 2 decades. For example, Van Nieuwenhuyse & De Koster (2009) propose an approximation approach for online order fulfilment systems with fixed and variable time window batching. Henn (2012) considers an online order batching problem to minimize the maximum order fulfilment time. To solve this problem, a heuristic solution algorithm is developed on a 1st-Come, 1st-Served basis. Pérez-Rodríguez *et al.* (2015) suggest an estimation of distribution algorithm for online batching problem to minimize turnover time of customer orders. Li *et al.* (2017) present a solution algorithm to solve a joint decision-making for online order batching and routing. Zhang *et al.* (2016) consider an online order batching to maximize the number of served customer orders for given fixed vehicle departure time. Zhang *et al.* (2017) deal with an online order batching and assignment problem to minimize turnover time. This study considers multiple pickers and time window batching to examine order picking performance under different numbers of pickers and customer orders and different levels of capability of pickers and order arrival rate. This study is extended by Zhang *et al.* (2018) to incorporate finite features of delivery operations. Alipour *et al.* (2020) improve the algorithm in Henn (2012) with multiple pickers and various rules for order batching, selection, and assignment. Giannikas *et al.* (2017) propose an order batching approach with similarity coefficient. The batching picking method develops a solution algorithm to deal with a situation where an order picking schedule is updated for newly arriving customer orders. Chen *et al.* (2018) suggest a non-parametric heuristic algorithm with order splitting for order batching. Gil-Borrás *et al.* (2021)

present a heuristic algorithm for the online order batching problem with multiple pickers. This problem considers 3 different objectives of minimizing order fulfilment time, order picking time, and different in workloads of pickers. Hossein Nia Shavaki & Jolai (2021) proposed a rule-based heuristic algorithm to solve order batching, picking and assignments and scheduling and routing of delivery vehicles at the same time. Each of the above literature studies order batching problems under different decision-making factors in terms of order picking resource and environment. For readers' convenience, Table 1 summarizes the details of the literature.

The results of the literature review show that the order picking has been widely studied with various constraints and objectives. In particular, it has been considered to deal with online customer orders with various types and quantities of items. However, to the best of our knowledge, the methodologies of the existing literature are the lack of applicability to order fulfilment operations in the Q-Commerce due to the following reason. Most of the previous studies consider the objective of minimizing the total order fulfilment time for a given set of orders, which can be valid for a large number of order fulfilment centers in reality. Nonetheless, such an approach does not guarantee that every order needs to be fulfilled in a very short period of time, e.g., a half of an hour. This implies that the extant order picking methods are not applicable to the Q-Commerce because they can fail to provide responsive delivery services for some orders. Obviously, this operational issue can be more serious when customer orders require various quantities and types of items in real time.

To address the limitations of the existing picking methods, this study contributes to academics by introducing a new approach to develop an order picking method. This approach uses the WAP analysis that a wide range of information regarding actual order picking activities and customer orders is explored to find the feasible order picking method for the Q-Commerce. This comprehensive analysis can be an alternative to the solutions that a high dimension of order picking environment should be incorporated into a decision-making framework for order picking development. A simulation model is also proposed to validate the new picking method by comparing with the current order picking method in real-world order fulfilment centers of the case study company. Some managerial implications on the new picking method are also derived later.

3. Case study

This section provides the understanding of order fulfilment activities in the case study company. The order fulfilment activities are explained in 2 subsections:
- the Sub-section 3.1 gives an overview of order fulfilment processes in a MFC;

Table 1. Summary of literature review on order batching

Literature	Order arrivals	No of pickers	Picking capacity	Order splitting	Batching method / solution approach
Van Nieuwenhuyse & De Koster (2009)	poisson process	n/a[**]	unlimited	allowed / not allowed	fixed time window batching; variable time window batching
Henn (2012)	exponentially distributed	single	limited	not allowed	1st-come 1st-serve saving algorithm with iterated local search
Xu *et al.* (2014)	Poisson process	n/a	unlimited	not allowed	1st-come 1st-served order; variable time window batching
Pérez-Rodríguez *et al.* (2015)	exponential distribution	single	limited	not allowed	estimation of distribution algorithm
Zhang *et al.* (2016)	exponential distribution	multiple	limited	not allowed	improved seed and saving heuristics
Li *et al.* (2017)	n/a	n/a	limited	not allowed	heuristics (similarity coefficient)
Zhang *et al.* (2017)	n/a	multiple	limited	not allowed	1st-come 1st-served order; heuristic based on similarity degree
Zhang *et al.* (2018)	exponential distribution	single	limited	not allowed	1st-come 1st-served order; saving algorithm
Alipour *et al.* (2020)	exponential distribution	multiple	limited	not allowed	1st-come 1st-serve order; saving algorithm with iterated local search
Hossein Nia Shavaki & Jolai (2021)	exponential distribution	multiple	limited	not allowed	heuristic based on similarly degree; saving heuristic and genetic algorithm
Gil-Borrás (2021)	n/a	multiple	limited	not allowed	variable neighbourhood heuristic
Current study	real-world data[*]	multiple	limited	not allowed	1st-come 1st-served order; workload balance-based order lines

Notes:
n/a – denotes that relevant information is not available in the corresponding study;
[*] – current study is done with real-world data obtained from MFCs in Korea;
[**] – means that relevant information is not available for the corresponding study.

- the Sub-section 3.2 performs the WAP analysis to discuss the fulfilment processes in more detail. Some important features of order picking activities in the fulfilment center are presented later.

3.1. Overview of order fulfilment process

This subsection describes the overall order fulfilment processes of the case study company. This company is one of the leading delivery service providers in Korea, which offers grocery delivery services from a network of 30 MFCs in dense cities such as Gyeonggi-do, Seoul-si, and Incheon-si. These cities have a population of 26.1 million people. Each of the fulfilment centers covers less than 3 km radius and fulfils each order within a half of an hour. Such a tight order fulfilment timeline is the core competitive edge of the delivery services in market. The fulfilment center delivers around 7000 kinds of items including fruits, salads, pet items and fresh foods from 9:00 am to 24:00 pm. During the operation hours, a pool of riders delivers items to customers. It should be noted that this company has a large number of riders to serve all customer orders to comply with the order fulfilment timeline. It means that this study rules out the possibility that the delivery services of the fulfilment centers are subject to the supply of riders. Figure 1 conceptualizes a network of the MFCs in the case company.

The MFCs are complex distribution centers for the quick delivery services. Each fulfilment center ranges from 5000 to 10000 ft^2 and has multiple zones for storage and retrieval of items. Each of the storage zones allows for certain kinds of items to be placed on bins and shelves. The center responds to customer orders in a real-time manner. Each of the orders involves 3 order fulfilment processes: picking, packaging, and delivery of items. Arrival of a customer order 1st initiates the picking process. The picking process begins with an issuance of a paper-based picking list of items. The picking list is a job order for a picker to retrieve items. The item retrieval requires the picker to visit and travel between different storage zones in the fulfilment center. Once all items of the order are collected, the order picking ends with a packing process at a packaging station. This station consists of several manual packers, each of which consolidates the items into a delivery box. Then, the box is placed on a shelf and waits for being picked up by a driver after the packing process. This means that the packing process is the last order fulfilment process done by the center. Afterwards, the rider delivers the box to its corresponding customer, and the order is completely fulfilled.

The MFC uses 1st-come 1st-served rule in terms of order fulfilment. The performance of the order fulfilment rule is measured as time spent to fulfil a customer order. Figure 2 presents a flow diagram of order fulfilment processes that a customer order goes through. This figure shows relationships between pairs of order fulfilment activities in terms of average processing time, i.e., total amount of time spent between the 2 activities. The processing times of the fulfilment activities are obtained from order fulfilment records for one month at the fulfilment centers of the case study company. As can be seen from the figure, it can be seen that the in-center order processing time (between the order receipt and the pick-up order) takes 12 min, while the delivery takes 18 min in average. In this way, the order fulfilment can be met with the timeline of 30 min. One thing should be noted that the effective order picking time (between the scanning list and the picking) takes 3.32 min in average, while involving high volatility as its standard deviation is 2.07 min. This implies that the complete fulfilment of a customer order is dependent on how the fulfilment center ensures fast and reliable order picking performance in practice.

Management of the order picking is crucial for integrity of quick delivery service. This management starts with an understanding of customer orders. According to the case company, it is found that each of the fulfilment centers has served around 1500 customer orders per day. In addition, each order requests a delivery of 5.37 items in average. Therefore, about 8000 pick-ups occur in the fulfilment center during a day. In general, each fulfilment center has 18...20 pickers during working hours. The number of pickers varies according to changes in order arrival rate over time. Figure 3 depicts the time-varying rate of order arrivals for a MFC in the case company. This figure shows that each fulfilment center handles different numbers of customer orders at different time intervals. This fluctuation leads to large variance ranging from 13% to 24%. This indicates 2 things. 1st, the fulfilment center needs to be flexible to process different levels of order arrivals in a day. This is because the rate of order arrivals reaches peak during the evening and late-night hours (from 18:00 pm to 24:00 pm), while it becomes stable at a lower level during the morning and early afternoon hours (from 9:00 am to 15:00 pm). 2nd, the high variance of the order arrival rate can be a burden for the fulfilment center to meet a tight order fulfilment timeline.

The manual order picking system has an advantage in serving customer orders with high variability in terms of order quantity and item type. According to De Koster *et al.* (2007) and Grosse *et al.* (2017), about 80% of fulfilment centers use the manual order picking due to its high flexibility. This advantage has gained more attention when automation devices are not applicable for pickers for order fulfilment. However, the manual order picking has several drawbacks as well. 1st, the time it takes for a picker to retrieve items can vary as customers place orders of various items. Because different kinds of items are located in different storage zones, the picker needs to spend longer time to complete item retrieval (Pyle, Zanetti 2021). Therefore, it becomes a challenge for the fulfilment centers to ensure a tight order fulfilment timeline in reality. 2nd, it is hard to maintain reliable order picking performance due to lack of skilful pickers. Many pickers have short tenure and leave their job before they reach a competent level of performance. For this reason, it creates a risk for the fulfilment centers to face order fulfilment delay.

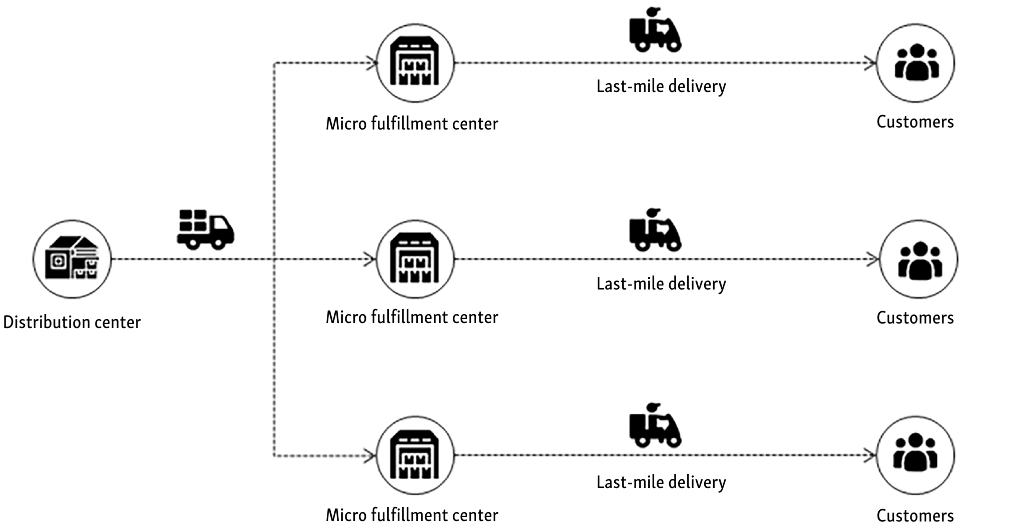

Figure 1. A network of last-mile delivery services in the case company

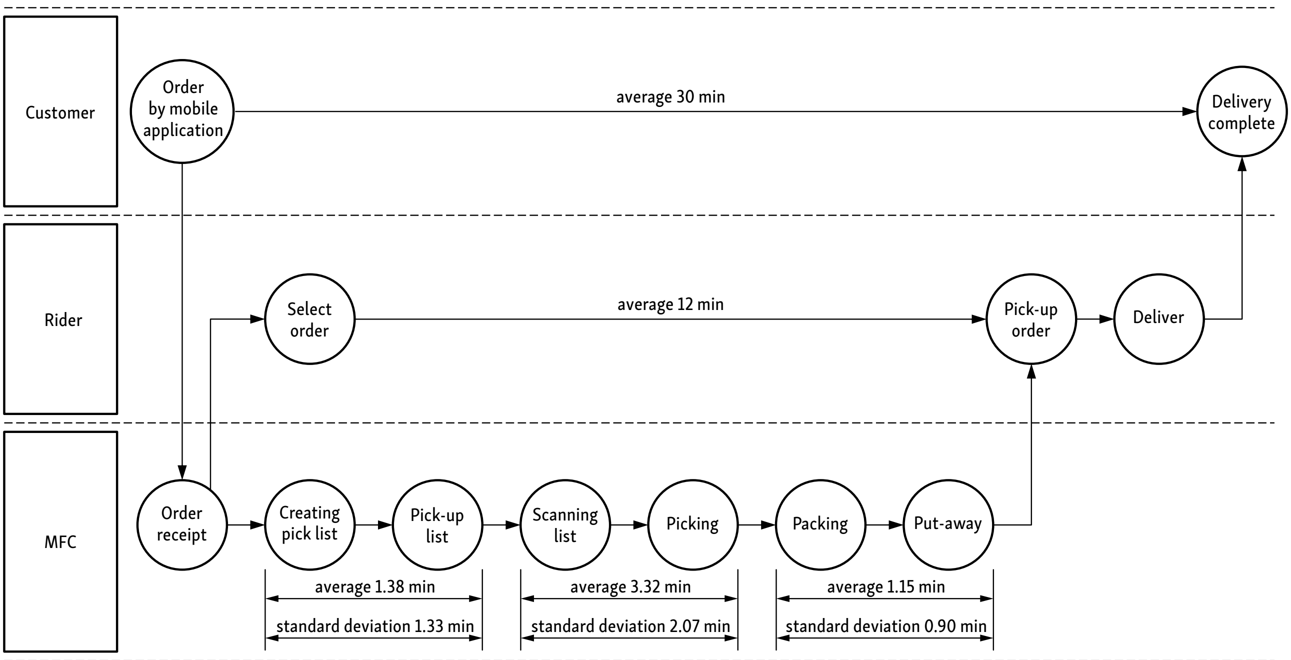

Figure 2. Time flow diagram of order fulfilment activities in MFC

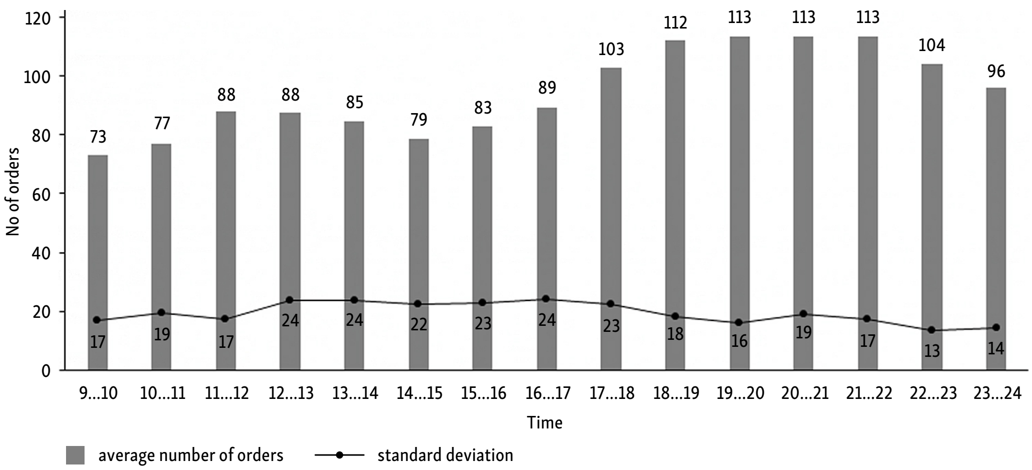

Figure 3. Arrival rates of customer orders for MFC in different time intervals

3.2. Order picking analysis

The delay concern calls for the development of a new order picking method. In this study, this concern is addressed by the WAP analysis. This analysis maps out important aspects of order picking environment in the fulfilment centers, from which it draws guidelines for the development of the new picking method (Lange 2020). Following the study of Park (2011), this study investigates the picking environment by considering the following 5 factors: order line distribution, picking time distribution, order arrival distribution, affinity grouping, and order picking activity distributions.

The order line distribution refers to a distribution of the number of kinds of items per customer order, i.e., order lines. Recall that the variability in item composition affects order picking performance because pickers need to travel different storage zones for item retrieval. In this sense, the distribution can give us insights into what type of order picking is desirable for the fulfilment centers. For example, if the number of order lines is large, it is better for a picker to use a SOP method. On the other hand, if it is small, a batch picking method is more viable to serve more than one customer order during a picking trip (Chen *et al.* 2018). Figure 4 shows the distribution of order lines per customer order in the MFCs. In the figure, the *X*-axis represents the number of order lines per customer order, while the left- and right-sides of *Y*-axis denote the number of customer orders that arrive to the center and their cumulative ratios during a day. Figure 4 presents that small-sized orders with less than 6 order lines account for about 60% and large-sized orders with greater than 10 order lines just take 4% of the total number of customer orders. This implies that a batch picking can be an alternative to the single one in the fulfilment centers. This is because the batch picking can reduce repetitive and inefficient SOP in dealing with large number of customer orders with few order lines.

Picking time distribution refers to the amount of time to serve each customer order with different order lines. Thus, this time distribution describes changes in order picking performance in the presence of variability in customer orders. Figure 5 presents the time distribution under the SOP in the MFCs. In this figure, the *X*-axis is the number of order lines per customer order, while the *Y*-axis indicates the time spent for retrieving all items of a customer order. The time distribution reveals 2 things:

- 1st, it tends to increase with the order lines. The picking time smoothly increases with low levels of order line, but it becomes to involve volatility when the order line is more than 20. This implies that the SOP has limitations in fulfilling customer orders with excessive variability;
- 2nd, it is also shown that the SOP needs to spend at least 2.5 min to deal with a customer order. In other words, it is hard for the fulfilment centers to strictly adhere to their short order timeline with the SOP when multiple customer orders arrive at the same time. This means that a batch picking method can be valid as it allows pickers to save time from repetitive trips to the storage zones.

Implementation of a batch picking requires an understanding of a proper order batch size. The batch size refers to the number of customer orders that a picker fulfils during a single trip. The batch size is affected by various factors such as number of pick aisles, length of pick aisles and arrival rate of customer orders (Xu *et al.* 2014). In particular, the order arrival rate plays a crucial role in determining the batch size. Table 2 shows order arrivals in the MFCs for 5 different time intervals: 5 min, 10 min, 15 min, 20 min and 25 min. This table shows minimum, average, and maximum arrival rates of customer orders for each time interval. For example, the number of customer orders that arrive to a MFC is 7.9 in average, while its minimum and maximum are 4.9 and 10.6, respectively, for the time interval of 5 min. Table 2 indicates that the batch picking needs to be done with the small batch size. Any batch size with more than 10 customer orders is likely to incur waiting time longer than 10 min. In this case, no quick delivery service is possible due to the tight order fulfilment timeline. Therefore, a feasible batch size exists within the time interval of 5 min. In other words, the batch size should be less than 8 customer orders in practice.

In general, the batch picking comes with a certain rule about which customer orders need to be picked together. This concern has motivated many studies to find frequent combinations of Stock Keeping Units (SKUs). The SKU is a unique identifier to specify characteristics of a kind of item in terms of size, colour, and quantity. Therefore, pickers can reduce their travel time for item retrieval when certain combinations of SKUs are often found in different customer orders. However, this approach seems not to be appropriate for the case company due to excessive variability in customer orders. To see this, Table 3 shows results of the SKU combination analysis over customer orders during a month. In this table, the frequency of a SKU combination denotes the number of customer orders having the same pair of SKUs, while the number of SKU combinations refers to the total number of pairs of SKUs corresponding to a certain SKU frequency interval. For example, there are 381915 SKU combinations that are found once across all the orders. This means that those combinations are found in none of pairs of customer orders. Meanwhile, it is also seen that there are 2291 SKU combinations, each of which is found between 301 to 420 times over the orders[①]. As can be seen from Table 3, it is interesting that it is hard to find common SKU combinations among the orders. More than 50% of SKU combinations are presented once over the orders, while very small portions of SKU

① For readers' convenience, a simple example of the SKU combination analysis is given here. Suppose there are 2 customer orders. The 1st order requests A, B, and C items, while the 2nd one has A, B, and D items. Thus, the 1st order has 3 SKU combinations as (A, B), (A, C), and (B, C). The 2nd one also has 3 SKU combinations as (A, B), (A, D), and (B, D). As a result, it is seen that there is only one SKU combination (A, B) found in both orders, but the other 4 SKU combinations do not. In this case, the frequency of combination (A, B) is 2, while the one of the others is given by one.

combinations are found in different customer orders during a month. This shows that a SKU-based batch picking rule is not desirable for the fulfilment centers. Indeed, this is one of the major characteristics of the Q-Commerce. Because customers can access items from a wide range of online stores across Internet, it is natural that customer orders differ from each other with respect to SKU. This leads to the fact that batch picking methods in the extant literature are unlikely to be applicable for the Q-Commerce.

Overall, the above analysis gives 2 implications. 1st, it is found that there is room for a batch picking to deal with customer orders in the Q-Commerce. A large portion of the orders have few order lines. It means that the batch picking can be competitive as it reduces travel time of pickers for item retrieval, while being flexible in dealing with arrivals of customer orders in real time. 2nd, it is noteworthy that customer orders are less similar because they have few SKU combinations in common with each other. This fact leads to the necessity of development of a new batch picking rule different from the ones found in the extant studies. Furthermore, it should be noted the batch picking needs to be done with a small batch size because of the tight order fulfilment timeline. The larger batch size, the longer waiting time to initiate order picking. Thus, arrival rate of customer orders should be carefully considered for the order picking development.

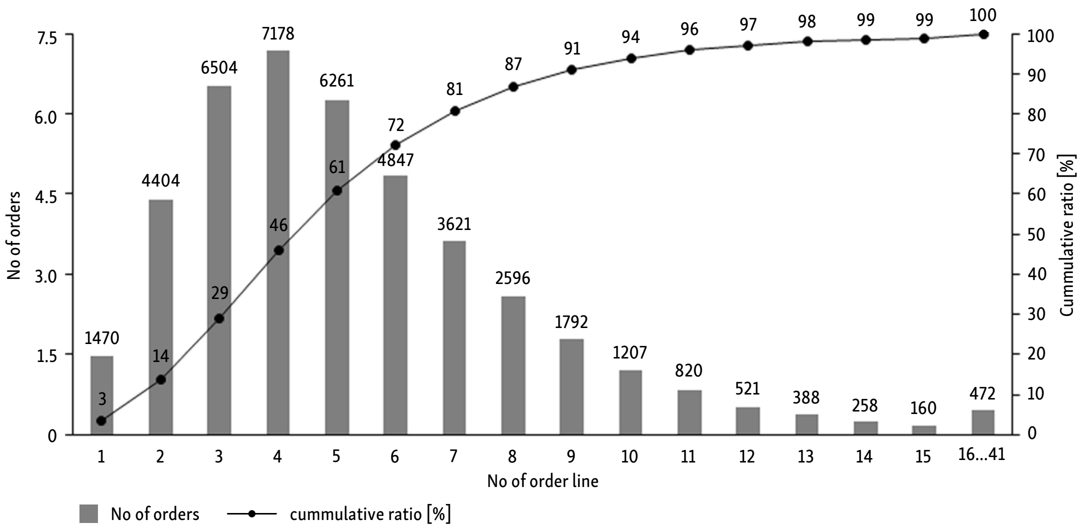

Figure 4. Order line distribution of daily customer orders in MFC

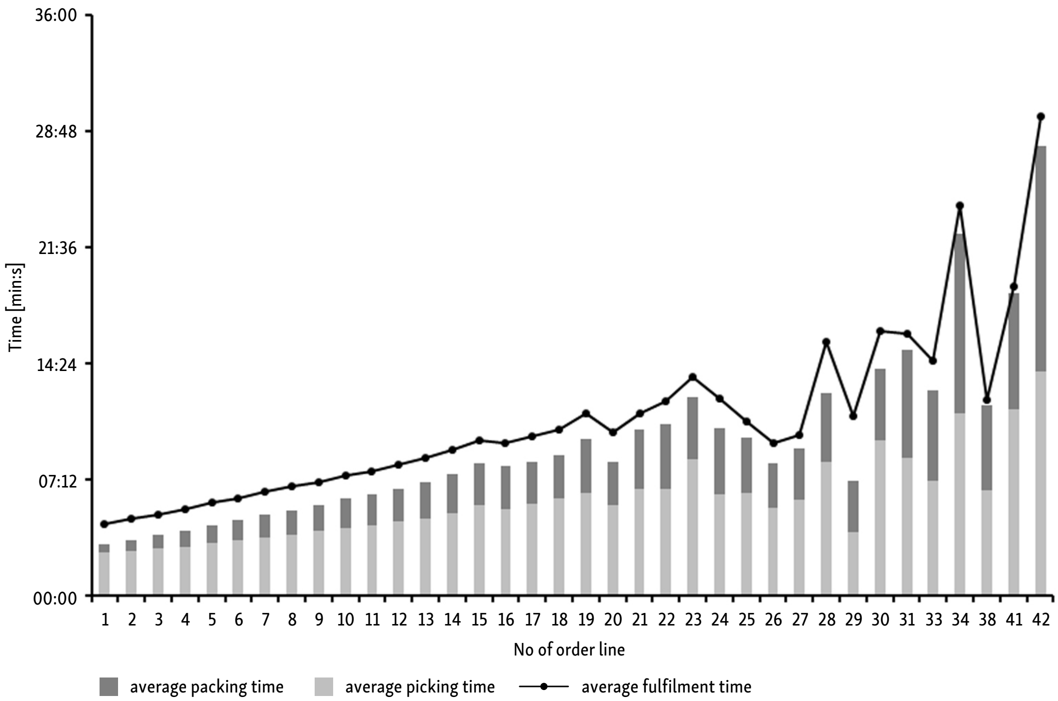

Figure 5. Picking time distribution in accordance with the number of order lines

Table 2. Arrival rate of customer orders

Time interval [min]	Number of customer orders		
	minimum	average	maximum
5	4.9	7.9	10.6
10	10.1	15.7	20.7
15	15.5	23.6	30.1
20	20.9	31.5	39.4
25	26.3	39.3	48.9

Table 3. Analysis of SKU combinations for the MFCs

Frequency of a SKU combination*	Number of SKU combinations**	Ratio [%]
1	381915	54.20
2	108690	15.40
3…5	105486	15.00
6…30	83064	11.80
31…60	9297	1.30
61…180	7227	1.00
181…300	6826	1.00
301…420	2291	0.30

Notes:
* – frequency of a SKU combination refers to the number of customer orders having a same pair of SKUs;
** – number of SKU combinations refers to the total number of pairs of SKUs corresponding to a certain SKU frequency interval.

4. Development and validation

Considering the results of the WAP analysis, this study proposes a HOP method. The hybrid method uses both a SOP and a batch order picking methods under the 1st-come 1st-served order fulfilment rule. Afterwards, this study suggests an agent-based simulation model to evaluate the performance of the hybrid method. For the development of the hybrid method, it should be noted that this study performed preliminary investigations with real-world order picking records of the case study company. These investigations find the best feasible order batch size and batch assignment rules. To focus on how the hybrid method works, this section does not provide a discussion of the preliminary investigations.

4.1. Order batching approach

The hybrid method needs to solve the following 2 decision-making issues:

- how many customer orders are assigned to the same batch;
- which customer orders need to be served by the batch picking method.
- To do this, the hybrid method facilitates a rule-based decision framework for selection between the SOP and batch picking methods. This selection varies depending on variability of customer orders as in Table 4. Table 4 shows that there are 25 combinations, each of which represents a pair of 2 customer orders. Each customer order corresponds to one of the 5 order line segments from D1 to D5. Each of the segments shows an order line interval between 1…2, 3…4, 5…6, 7…8 and above or equal to 9, respectively. In this table, the term S indicates that the hybrid method uses the SOP, while the term B means that the batch order picking is applicable to deal with customer orders in the corresponding combination.

This study considers that the single picking is desirable when 2 orders come with relatively high number of order lines. This approach gives pickers to save item retrieval time. However, if the sum of order lines from 2 orders is less than or equal to 10, the batch picking tends to show better performance to reduce picking time. When it comes to the selection of orders for the batch picking, this study considers the following several issues[1]. 1st, it should be noted that orders with more than 10 order line have the risk of late fulfilment due to long order picking time. Therefore, a batch picking for the orders is not practicable to ensure the tight order fulfilment timeline. 2nd, the total time for a batch picking should be less than 10 min for successful order fulfilment in the case study company. To be more specific, as can be seen from Figure 2, a fulfilment center has on average around 10…12 min to perform an order picking operation. It means that a combination of 2 orders for batch picking should be fulfilled within that time. However, the average picking time of an order tends to increase with the number of order lines as presented in Figure 5. For this reason, this study considers that a batch picking selects 2 orders where the sum of their order lines is less than or equal to 10. Note that the batch picking decision does not have narrow applicability in the case study company because the number of orders with less than or equal to 10 order lines accounts for 94% of the total number of orders in the center as shown in Figure 4.

For better understanding of the above decision framework, Figure 6 provides an illustrative example of the hybrid method in online contexts. This figure shows that there are 4 customer orders arriving at a fulfilment center at different time. Each of the orders has different number of order lines. To be more specific, the 1st and 2nd orders have 3 and 2 order lines, respectively, while the 3rd and 4th ones have 8 and 12 order lines, respectively. Given the decision framework in Table 4, it is seen that the 1st and 2nd orders can be done with the batch picking. Therefore, those 2 orders are combined into a batch and assigned to the 1st picker on standby. Meanwhile, the 3rd and 4th customer orders are not appropriate for the batch picking because they have large number of order lines. Thus, these 2 orders are assigned to 2 other pickers, respectively.

[1] The selection of orders for batch picking also needs to consider the possibility of human error during order picking operations. This is because pickers are prone to cause more picking errors as they pick items for orders with a number of order lines in practice.

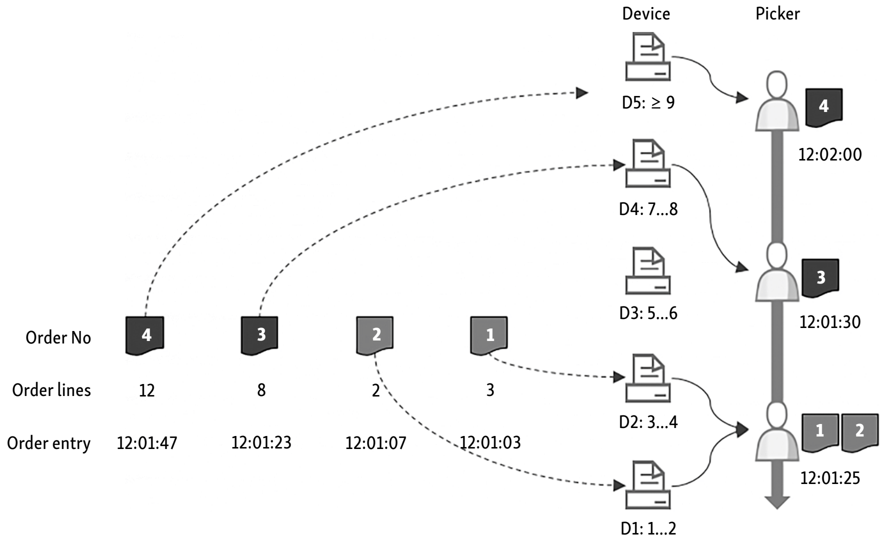

Figure 6. A concept of the HOP method

Table 4. Decision framework for selection between the SOP and batch order picking

Number of order line → ↓		1…2	3…4	5…6	7…8	≥9
	Segment*	D1	D2	D3	D4	D5
1…2	D1	B**	B	B	B	S
3…4	D2	B	B	S	S	S
5…6	D3	B	S	S	S	S
7…8	D4	B	S	S	S	S
>9	D5	S	S	S	S	S

Notes:
* – each of the segments D1, D2, D3, D4, and D5 denotes an order line interval between 1…2, 3…4, 5…6, 7…8 and above or equal to 9, respectively;
** – S and B stand for the SOP and batch order picking methods, respectively.

4.2. Simulation model

This subsection performs numerical experiments to evaluate performance of the hybrid method. The performance evaluation is done by comparison with the SOP method as the current practices in the MFCs of the case company. This study develops an agent-based simulation model for the comparison of the 2 picking methods. According to interviews with pickers in the fulfilment centers, the simulation model needs to consider 4 things:

- 1st, customer orders are not known in advance. This online environment implies that the pickers are not aware of items in customer orders before they show up in order picking lists;
- 2nd, picking capacity of a picker is not considered. This indicates that physical constraints in order picking resources, i.e., picking basket and picking aisle congestion, are not incorporated in the simulation model;
- 3rd, it is assumed that the pickers choose the shortest path to retrieve items. It means that the simulation model knows travel distance and corresponding picking time for every pair of storage locations of items[1] in advance;
- 4th, picking error is not considered.

The simulation model uses the commercial simulation software ARENA 15.1 (*https://arena.informer.com/15.1*) operated on *i*7-12700K CPU@3.61GHz. This software allows us to run an agent-based model to describe order picking activities by a group of pickers. Each customer order is defined a set of information about order entry time, items, quantities, and their storage locations. Each of the storage locations is associated with a layout of shelves where items are kept for retrieval. For better understanding of the storage locations, Figure 7 shows the MFC layout in the simulation model. The center has a group of storage zones, each of which consists of 4…10 shelves adjacent to each other. Each picker takes an order picking list from the order-list picking point and travel between the storage zones. The picking path is depicted in solid lines across the fulfilment center. Once the picker completes item retrieval for a customer order, he packs the items into a box at the packing station and hands over it to a rider for last-mile delivery.

Recall that order picking performance is highly affected by exogenous various factors regarding order picking environment. To see this, the simulation model generates 6 scenarios from real-world order picking records of the case company. Each of the scenarios has different arrival rate of customer orders during a day and the numbers of order lines per order, SKUs, item pick-ups, pickers and packing stations as shown in Table 5. When it comes to the number of pickers, each picker has different working hours. The number of pickers varies with time intervals. For example, in case of Scenario 1, this table shows that there are 4 pickers working for 6 h between 9:00 am to 15:00 pm.

[1] Floyd–Warshall algorithm is used to obtain the shortest path between a pair of item storage locations in the study.

Table 5. Descriptions of the 6 scenarios for the performance evaluation

Parameters		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Arrival rate of customer orders		1153	1617	2018	2321	3059	3871
Average number of order lines per order		5.12	5.47	5.49	5.05	5.58	5.46
Number of SKUs		2037	2534	2784	2896	3445	3546
Number of pick-ups		5904	8852	11071	11712	17080	21129
Number of pickers	09:00...15:00	4	5	6	7	8	9
	09:00...16:00	0	1	3	4	4	6
	15:00...24:00	5	6	7	8	9	10
	16:00...01:00	3	3	3	3	5	7
	Total	12	15	19	22	26	32
Number of packing stations		5	5	5	7	7	7
Time period [1 day]		15 h (9:00...24:00)					
Area of order picking place [ft^2]		9000					

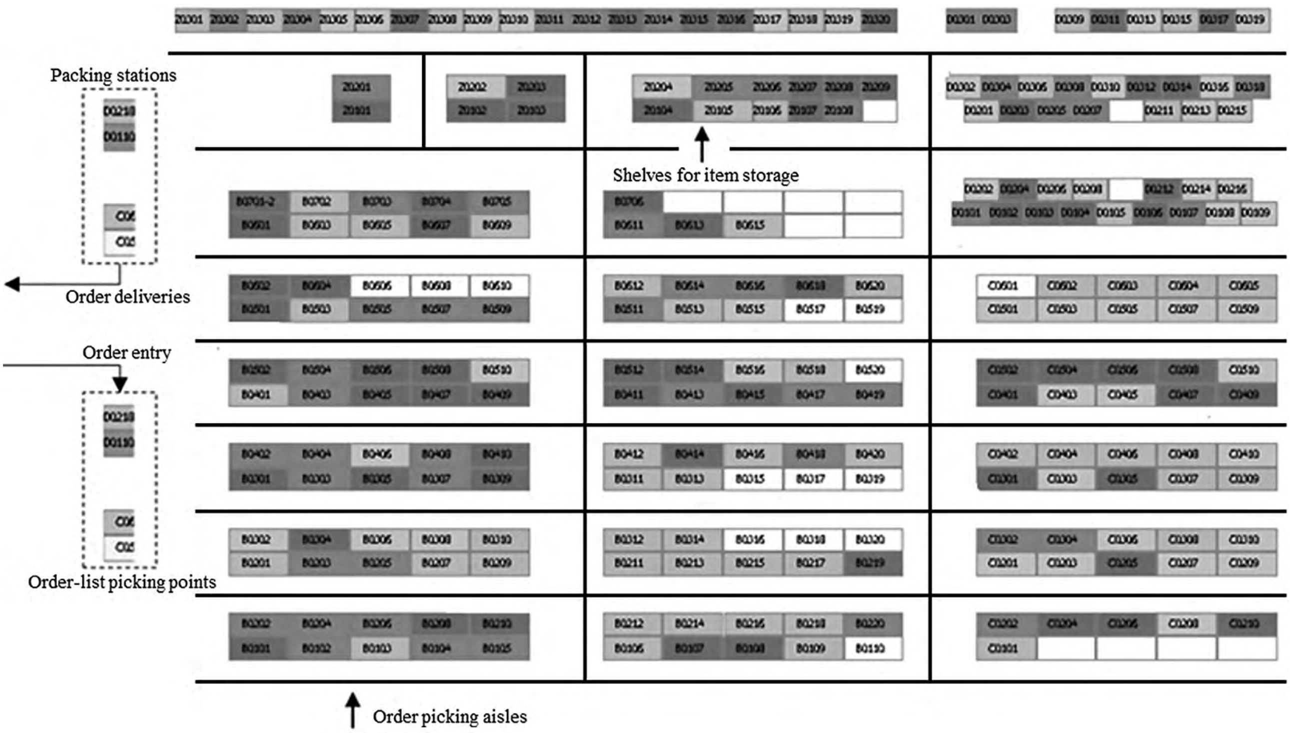

Figure 7. The MFC layout in the simulation model

Afterwards, 8 pickers newly come to the center, 3 of which works until 1:00 am, while the other ones leave at 24:00 pm. The larger scenario number, the more customer orders arrive. Thus, the simulation model can evaluate the performance of the SOP and batch order picking methods with a variety range of order arrival rates. Each picker has a certain order picking capability. The simulation model defines the capability as a function of amount of times to pick and pack items for a customer order as shown in Table 6. Tables 5 and 6 shows that pickers show different performance in different order picking and packing environments.

Table 6. Parameters for order picking capability of each picker

Parameter	Value
Travel speed [m/s]	0.83
Fixed time of picking process [s]	8
Fixed time of packing process [s]	21
Picking time in frozen storage zones [s]	11.2
Packing time in frozen storage zones [s]	11.0
Picking time in ambient and chilling storage zones [s]	10.2
Packing time in ambient and chilling storage zones [s]	7.9
Number of packing stations	5

4.3. Results and discussions

Given the above parameters, Table 7 summarizes the results of the performance evaluation for the SOP and HOP methods for the 6 scenarios. For brevity, each of the picking methods are denoted by SOP and HOP, respectively. It is noteworthy that the SOP method has been used in the MFCs of the case study company. Therefore, the comparison between the 2 picking methods shows how and how much the hybrid picking method is superior to the single one. This implies that the performance evaluation validates the competence of the hybrid picking method in this study. The results of the performance evaluation are also summarized by variance and standard deviation across the scenarios in the table.

In this table, the performance evaluation results are measured by 2 metrics: time and order batching. The time measures consider 4 criteria: average waiting time, picking time, packing time, and order completion time. Here, the order fulfilment time is the total amount of time to serve a customer order in the fulfilment center. Clearly, the lower value of the time measures indicates a better performance of the corresponding order picking method. On the other hand, the order batching measures focus on the numbers of batch picking, i.e., the number of times that 2 orders are fulfilled by a picker during a single picking tour, and waiting customer orders, i.e., customer orders waiting for being fulfilled by pickers after arriving at the center. The greater number of batch picking, the more time pickers save to retrieve items for order fulfilment. Similarly, the smaller number of customer orders waiting for being processed, the less chance the fulfilment center fails to serve responsive delivery services to customers.

This table gives several implications on the both the SOP and batch order picking methods. 1st of all, in terms of the order batching measures, it is seen that the number of batch picking tends to increase with the arrival rate of customer orders. It means that the HOP method has more chance to find a greater number of pairs of customer orders for order batching as more customer orders arrive during a time interval. Furthermore, it is also found that the ratio of the number of batch picking to the total number of customer orders in a day increases with the order arrival rate. For the 6 simulation scenarios, the ratio is calculated as 2.8%, 5.7%, 7.4%, 8.4%, 9.5%, and 9.9%, respectively. This implies that the HOP method becomes more influential in dealing with the increasing number of customer orders during a day. In terms of the number of waiting customer orders, it is shown that the HOP method shows better performance than the SOP one. This indicates that the fulfilment center with the HOP method has the smaller number of orders in queue. Here, it should be noted that there is little correlation between the number of waiting orders and the average order picking time. Considering the scenario datasets in Table 5, it is also found that even the increase in the number of SKUs of customer orders does not significantly affects the reduction in the number of waiting orders. This implies that the decrease in the number of waiting orders is not attributed to the improvement in the order picking time, but to the greater capability of the HOP method in fulfilling a number of customer orders during a time interval.

Table 7. Simulation results with the SOP and HOP methods

Performance category*	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6		Variance (standard deviation)	
	SOP	HOP	SOP	HOP	SOP	HOP	SOP	HOP	SOP	HOP	SOP	HOP	SOP	HOP
Time measures [min]**														
Average waiting time [s]	0.24	0.17 (29.2%)	0.42	0.24 (42.9%)	0.78	0.37 (52.6%)	0.88	0.28 (68.2%)	1.24	0.39 (68.6%)	1.33	0.35 (73.7%)	0.16 (0.39)	0.01 (0.08)
Average picking time [s]	2.17	2.14 (1.4%)	2.17	2.11 (2.8%)	2.18	2.10 (3.7%)	2.11	2.03 (3.8%)	2.20	2.11 (4.1%)	2.17	2.08 (4.1%)	0.00 (0.03)	0.00 (0.03)
Average packing time [s]	1.02	1.02 (0.0%)	1.06	1.06 (0.0%)	1.07	1.07 (0.0%)	1.01	1.01 (0.0%)	1.08	1.08 (0.0%)	1.06	1.06 (0.0%)	0.00 (0.03)	0.00 (0.03)
Average fulfilment time [s]	3.43	3.33 (2.9%)	3.66	3.41 (6.8%)	4.03	3.55 (11.9%)	4.00	3.32 (17.0%)	4.52	3.57 (21.0%)	4.57	3.48 (23.9%)	0.17 (0.41)	0.01 (0.09)
Batch measures (orders)														
No of batch picking***	–	32 (2.8%)	–	91 (5.7%)	–	149 (7.4%)	–	194 (8.4%)	–	289 (9.4%)	–	384 (9.9%)		13983.1 (118.25)
No of waiting orders****	0.28	0.20 (28.6%)	0.73	0.40 (45.2%)	1.71	0.80 (53.2%)	2.20	0.67 (69.5%)	4.17	1.27 (69.5%)	5.65	1.42 (74.9%)	3.58 (1.89)	0.19 (0.44)

Notes:
* – SOP and HOP;
** – the value in parenthesis is the extent to which the HOP method shows better performance than the SOP one for the corresponding time measure. The value is calculated as 100 × (SOP − HOP) / SOP;
*** – the value in parenthesis represents the ratio of the number of waiting orders to total number of orders in a day;
**** – the value in parenthesis is the extent to which the HOP method shows better performance than the SOP one for the corresponding batch picking measure. The value is calculated as 100 × (SOP − HOP) / SOP.

When it comes to the time measures, it is seen that the HOP method has the shorter average order waiting time than the SOP one. It means that the HOP method reduces unnecessary waiting time of orders, enabling the fulfilment center to provide customers with responsive delivery services. Especially, as the arrival rate of orders increases across the simulation scenarios, the average waiting time with the SOP method increases from 0.24 to 1.33 min, while increasing from 0.17 to 0.35 min under the HOP one. This implies that because the HOP method deals with more customer orders than the SOP one within a time interval, it reduces the risk of order fulfilment delay. Therefore, the fulfilment center can improve the reliability of its order fulfilment performance. Such improvement in the order waiting time leads to the decrease in the average order fulfilment time. As can be seen from the table, the SOP method seems vulnerable to the increase in the order arrival rate because its average fulfilment time increases from 3.43 to 4.57 min over the simulation scenarios. However, in case of the HOP method, the average fulfilment time tends to be maintained at a certain level between 3.33 and 3.57 min. This indicates that the batch picking allows the fulfilment center to be robust to variations of the arrival rate of customer orders in reality. The table also shows that the HOP method contributes to the reduction in the average order picking time. This is because the batch picking enables pickers to spend less time on unnecessary picking tour in the storage zones. However, the HOP method does not bring a notable change in the average packing time compared with the SOP one.

5. Conclusions

Q-Commerce has opened a new avenue for on-demand delivery services. It allows customers to order items from online stores at any time, without being subject to certain purchase limits. Every order is fulfilled within a short time under the efficient order fulfilment process in the MFCs. In the fulfilment centers, the order fulfilment is highly dependent on manual-based SOP in these days. This picking method is susceptible to customer orders with various order quantities and item type and working performance of pickers. Such operational risks have led to an increasing attention from the fulfilment centers to consider a new order picking method. This study developed a HOP method to mitigate the operational risks. This new picking method combined SOP and batch order picking methods to preserve flexibility of order picking and reduce order fulfilment time. The idea of the order batching came from the results of WAP analysis. The analysis implications characterized patterns of customer orders in terms of arrival rate and order line and measured pickers' performance. The hybrid method was evaluated through numerical experiments with an agent-based simulation model under various scenarios.

This study finds that the WAP analysis is valid for designing an order picking method in a fulfilment center. The statistical information from the analysis provides meaningful insights into the development of the new order batching approach under various constraints regarding order picking environment. Through the simulation experiments with 6 datasets from the case study company, this study obtains several findings related to the hybrid method as follows. 1st, it is found that our batch picking approach shows reliable performance in terms of order fulfilment time even the order arrival rate increases during a day. This is possible because the batch picking improves the waiting and picking times for order fulfilment. 2nd, this study presents that the hybrid method shows robust performance in terms of the order fulfilment time. Although the average waiting time tends to slightly increase with the order arrival rate, the decrease in the average picking time contributes to maintaining the order fulfilment time in a reliable manner. This implies that the hybrid method can eliminate some unnecessary picking tours by handling 2 orders at once. 3rd, it is also shown that the hybrid method has a greater capability of dealing with a number of orders than the single picking one. This feature allows an order fulfilment center to have the smaller number of orders in queue.

Considering the findings of the current study, several future research directions can be identified as follows:
- 1st, it is meaningful to study an order picking method to handle customers' order cancellation and/or modification in real time;
- 2nd, a study on conventional warehousing problems (e.g., item allocation and inventory replenishment) can be also incorporated into a development of order picking method for Q-Commerce;
- 3rd, it is also valuable to study other order batching approaches to improve order picking efficiency and order fulfilment performance.

Author contributions

Kwang-Tae Kim, *Dong-Hoon Son* and *Hongchul Lee* conceived the study and was responsible for the design and development of the data analysis.

Kwang-Tae Kim and *Hyunwoo Kim* were responsible for data collection and analysis and interpretation.

Disclosure statement

The authors declare no conflict of interest.

Declaration on the use of Artificial Intelligence (AI)

During the preparation of this manuscript, the authors used *ChatGPT-4* to improve language clarity and assist with grammar checking.

The prompts used are "Please find the grammar errors and suggest alternative sentences".

The output from these prompts was used to enhance grammatical accuracy, improve sentence structure.

While the authors acknowledge the usage of AI, the authors maintain that they, *Kwang-Tae Kim*, *Dong-Hoon Son*, *Hyunwoo Kim*, and *Hongchul Lee*, are the sole authors of this article and take full responsibility for the content therein, as outlined in COPE recommendations and journal policies.

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