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An operation synchronization model for distribution center in E-commerce logistics service

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ABSTRACT

This paper is among the first that proposes a synchronization measurement model for the distribution centre operation synchronization (DCOS) problem, which aims to ensure the E-commerce order's punctuality and synchronization at the same time. The main motivation of DCOS is that the intensified competition in E-commerce market makes efficient E-commerce logistics service extremely important, which means saving logistics cost and ensuring customer service at the same time. The synchronized operation may be a possible solution to ensure efficient order transhipment in the distribution center and to save cost. We thus introduce a measurement approach that is able to address the distribution center operation synchronization (DCOS) problem such as the trade-off relationship between synchronization and punctuality. In order to get persuasive conclusions, we adopt data from a real practice case and apply CPLEX to get the optimal solution. Our computational results show that considering the asynchronous cost in the total cost objective function will greatly improve the operation synchronization in the distribution center, by saving the storage space, the equipment, and the labour resources. And if the storage cost is in a reasonable range, the synchronized operation can be realized while the punctuality is also optimized. It is found in our case that the most efficient way to improve distribution center operation is expanding inbound operation capacity.

1. Introduction

The fierce competition in the E-commerce business has triggered a strict service-oriented market. As a result, the E-commerce logistics service provider has to face the challenge of providing reliable and customized delivery service to meet diverse requirements from the huge E-commerce customer base while keeping operation costs low. And the logistics service for e-commerce order fulfilling becomes a bottleneck in the industry because of followed reasons: The logistics providers have to deal with enormous order fulfillment tasks at one time as millions of simultaneous order buttons are clicked online; the logistics providers need high flexibility of processing capacities to meet the explosive order demands which occur during festival and special selling days; the logistics providers are faced a complex order fulfilling scenario, as the e-commerce suppliers and customers are geographically dispersed and the e-commerce orders are always small but with high varieties. Successful E-commerce businesses rely heavily on efficient logistics services because of the enormous number of small-batch orders relating to geographically dispersed customers and suppliers who have high expectations regarding service [27]. And it is hard for logistics providers to expand their capacity at a short time to adapt the quick growth order processing requirements. So, how to use existing resources more efficiently is a more feasible solution. In this paper, we provide synchronize as a new solution to make more effective operation and fluent order transshipment in distribution center. The distribution center is one of the key transhipment nodes within the logistics service network [17,4]. As shown in Fig. 1, bulky packages are transported from separate suppliers to the distribution center [61]. Here the packages are broken down into smaller units at a receiving area. These are then processed in a sorting area where products are picked according to the order information. According to their destinations, the unit products are now recombined in a consolidation area and loaded onto a specified outbound truck in a shipping area for last mile delivery.

Most research points out that synchronization is the critical factor in finding an optimal solution for distribution center operations [60]. If inbound and outbound truckloads are synchronized, staging storage can

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be kept to a minimum level and it is easier to ensure on-time delivery [17,4,49,8]. At the same time, synchronization helps to increase the throughput rate in the distribution center and gets rid of the costs associated with longer-term storage and the retrieval of goods [2].

There are a number of different possible approaches to synchronize operations [9]. One of the most promising approaches, put forward by Chen et al. [22], focuses on synchronization in production scheduling. However, the problem of synchronization is not considered in distribution centers where E-commerce is the primary business model. In this paper, we therefore focus on the distribution center operation synchronization (DCOS) problem as it relates to E-commerce. In the DCOS problem limited resources are allocated according to some reasonable principles so as to ensure quick and effective transshipment of products in the distribution center. This happens under different constraints including time, storage space, equipment and workforce. In this study we introduce a synchronization measurement index because the temporary storage for consolidating packages places a strict constraint upon how perfectly synchronization can be measured [9]. This measurement index also reflects the utilization of temporary storage areas and other relevant limited resources in the distribution center.

The main contributions of this study are as follows. First of all, synchronization performance in distribution centers is specifically related to E-commerce scenarios. The E-commerce order is fluctuant during the special selling season, and the number of E-commerce orders continues booming, the synchronized operation is an important way to conquer this challenge, as it tries to make maximum use of limited resources to fulfill E-commerce orders. Secondly, it introduces an approach to work out the measurement that is able to address the distribution center operation synchronization (DCOS) problem. In order to do this, we examine both synchronization and punctuality so as to figure out the trade-off between them. Some of our observations are particularly significant for the optimization of E-commerce distribution center operations. Notable here is the fact that if a synchronization penalty is applied, better operation scheduling in the distribution center can be achieved. This, in turn, can have the benefit of increasing the efficient utilization of temporary storage space, equipment, and the workforce.

The rest of this paper is organized as follows: Section 2 reviewed related literature and listed the research gaps from four aspects. Section 3 built up the mathematical model, while Section 4 designed the experiment case and made a comparative analysis. Section 5 summarized the conclusion from the experiment results and gave suggestions for future research.

2. Literature review

In this section, prior studies related to the distribution center operation problem are reviewed. We outline the significance of previous achievements in this research area and indicate some research gaps. Based on these gaps, we have divided all of the related work into four parts: the research background; the optimization objective; the research problem model; and the methodology.

2.1. The research background

The distribution center operation problem has been studied in multiple industrial areas. These include the optimization of distribution center operations for logistics providers for: less-than-truckload (Bartholdi and Gue); freight terminals [26,14,6,19,41,23,38,37,38,37,39]; mail distribution centers [43]; and other logistics companies [51,52]. Some researchers have also looked at refrigerated foods and other perishable products [28,15,3,55,50] and fast-moving consumer goods [33] where there is a particularly strong requirement for high quality logistics services. Here, researchers have paid close attention to the synchronization of inbound and outbound flows at cross docking terminals (products are received and fast transhipped in this terminal) so as to reduce the total operation cost and ensure reliable delivery. However, few researchers have looked at distribution center operation optimization for E-commerce logistics provider's, despite the fact that logistics is the backbone of the booming E-commerce business [24]. In addition to this it should be noted that distribution center operations in E-commerce are much more complex. This is not only because of the characteristics of E-commerce orders, but also because E-commerce customers have higher expectations regarding logistics services.

Research Gap 1: Because of the boom in E-commerce and the lack of studies on E-commerce logistics distribution center there is an urgent need to develop an effective scheduling solution for E-commerce logistics at the transhipment node.

2.2. The optimization objective

To ensure efficiency in distribution centers, most current inbound and outbound flow scheduling models try to minimize the total operation time. This starts when the first cargo is unloaded from an inbound truck and ends when the last consolidated order has been loaded on an outbound truck [14,6,48,41,20,21,15,3,4,39,45,47,34,46]. Others focus on minimizing the total travel distance for all forklifts or cargo transfers [51,52,26,35,43,30,19,23]. Some researchers have looked at how to minimize total operational cost, which may include: inventory holding costs; labor costs; and scheduling sequence setup and change costs [28,33,38,37,44,7,11]. Others have explored how to minimize penalties for lack of punctuality [31,12]. Some have even broadened the scope and examined how to minimize both total operational cost and the penalties for lack of punctuality [35,42].

Research Gap 2: Although many studies have evaluated the efficiency of distribution center operations, there are limited studies that examine how to synchronize workflows, which is considered to be the most important factor in ensuring logistics service quality and keeping low cost [1]. In synchronization operation scenario, not only the operation time should be considered, but also the time of occupying the resources which include the inbound/outbound door, storage space, operation equipment, and human labor should be limited.

2.3. The research problem model

As shown in Table 1, previous research on the distribution center/cross-docking scheduling problem has mostly developed models that are based on the following assumptions: 1) The principal sorting mode in distribution centers is forklifts operated by workers. However, nowadays automatic sorting conveyor systems have been applied widely in logistics centers, and this has attracted the attention of several researchers. In the case of manually operated systems the model has to consider workforce limitations, cargo travel distance, and congestion problems. These are generally irrelevant in the case of automatic conveyer systems. 2) Some papers are based on scheduling models upon there being a single receiving and shipping door in order to generate fundamental insights. Others base their models upon multiple inbound and outbound doors, which is closer to real practice. 3) Generally, distribution centers will allow temporary storage in the staging area. Here the buffer space limitation is not a significant constraint because all cargos have strict limits upon how long they may stay in storage (e.g. less than 24 h in Walmart's cross-docking center). For products requiring extremely fast transhipment, such as refrigerated/perishable foods, zero inventory constraint assumptions are made in any related cross-docking scheduling models. 4) One of the most important functions of a distribution center is to consolidate orders to achieve full truckloads. Most studies therefore assume that an outbound truck will not leave until it is full or all of the orders have been loaded. However, for some logistics companies, the in/out flow rate of the distribution center is relatively steady. In this case they prefer fixed scheduling of in/out trucks. As a result several researchers have produced models where outbound trucks are dispatched at a fixed time.

Drawing upon most current real-world examples of E-commerce distribution centers, some assumptions are made: an automatic sorting system; multiple in/out doors; and a temporary storage buffer. We also assume that outbound trucks will have to wait until all orders are loaded.

Research Gap 3: The scheduling problem model presented in our paper is based upon real-world E-commerce distribution centers, which is scarcely reported and can reflect the existing E-commerce order characteristics of the distribution center.

2.4. The methodology

Various methodologies have been used to tackle the distribution center scheduling problem. Drawing upon the just-in-time dynamic truck scheduling model built for cross-docking, and using a mixed integer linear programming model [10], a number of researchers have applied an heuristics methodology for the solution [31,56,12,23,29,25,45,34,46]. Others have used combined methodologies such as an heuristics algorithm plus simulations or dynamic programming [26,6,35,35,30,41,38,37,38,37,42,15,3,4,39,16]. Some studies have even applied three or more methodologies in order to find better solutions [2,53,1]. In our paper, in order to generate basic knowledge of the synchronization model needed for distribution center operations, CPLEX is examined for obtaining an optimal solution.

Research Gap 4: Model is focusing on E-commerce distribution center operations with the objective of synchronization are limitedly reported.

3. The model

3.1. Problem description

This paper takes as its basis an E-commerce distribution center with a fixed number of inbound and outbound bays. Inside the center operations are mainly processed via an automatic sorting system. As a result, workforce limitations can be ignored. All inbound trucks arrive at the distribution center yard at their scheduled time, and each outbound truck must wait until all orders are loaded but still has a suggested departure time. All cargos carried by inbound trucks have an appointed destination according to the E-commerce orders placed by customers. The required operation time for each inbound and outbound truck is also known in advance. In our model, there is a one-to-one correspondence between the recombination task j and the outbound truck j.

The complete operation process in the distribution center includes receiving, sorting, consolidating, and loading the recombined cargos for shipping. In our model we divide the whole process into two stages. The first stage refers to unloading cargos from inbound trucks and sending them to the sorting system. The second stage is recombining cargos according to customer orders and loading them on the specified outbound trucks for shipping. This division is based upon our recognition of the fact that the distribution center operation synchronization (DCOS) problem can be modelled as a two stage machine scheduling problem, about which there is already an abundant literature [58]. Our model is therefore based on Li, Lim and Rodrigues's JIT scheduling model with time windows [31].

First of all, in our model, some practices are considered that, unforeseen circumstances always arise after scheduling schemes are established. It is a common requirement from distribution center dispatchers that dynamic situations can be handled within the scheduling model. For instance, a dispatcher may want to be able to adjust a truck's priority for an urgent new customer order. As a result, we have incorporated two main decision variables, y_{ir} or Y_{ir}, to represent the operational precedence of inbound or outbound trucks. By applying these two variables the scheduling scheme can be transferred from inbound and outbound operational task scheduling at specified operation bays to task scheduling within an overall task pool.

Secondly, WT_j is introduced to represent the longest waiting time for the recombination task j, which is the time between when the first and the last related cargo arrives at the consolidation area. We have adopted this variable to measure the degree of synchronization attributable to the scheduling scheme.

Thirdly, two penalty factors are brought into the objective function. α represents a penalty factor for not being punctual, β represents the combination area's unit storage cost. By changing the value of these two factors, we can simulate punctuality-oriented or synchronization-oriented operations.

3.2. Model formulation

The notations used in the model are as follows:

α is the penalty cost for lack of punctuality per unit, representing time-related earliness or tardiness
β is the storage cost for the unit combination area per unit of waiting time
M is the number of inbound trucks
N is the number of outbound trucks
K is the number of inbound bays
L is the number of outbound bays
$V_{ij} = 1$ if inbound truck i contains cargos that are required by outbound truck j, for $i = 1,\ldots,M$; $j = 1,\ldots,N$
PI_i is the process time required to unload all cargos from inbound truck i, $i = 1,\ldots,M$
PO_j is the process time required to load all orders to outbound truck j, $j = 1,\ldots,N$
Pdt_j is the planned departure time of outbound truck j, $j = 1,\ldots,N$

Decision variables:

$y_{ir} = 1$ if the inbound truck is ranked in the r^{th} place, for $i, r = 1,\ldots,M$
$Y_{ir} = 1$ if the outbound truck is ranked in the r^{th} place, for $i, r = 1,\ldots,N$
$x_{rs} = 1$ if the inbound trucks which ranked in the r^{th} and s^{th} place are processed at the same bay, and the r^{th} truck immediately precedes the s^{th} truck, for $s, r = 1,\ldots,M$ and $r < s$
$X_{rs} = 1$ if the outbound trucks which ranked in the r^{th} and s^{th} place are processed at the same bay, and the r^{th} truck immediately precedes the s^{th} truck, for $s, r = 1,\ldots,N$ and $r < s$
St_i is the processing start time for inbound truck i, $i = 1,\ldots,M$
Dt_j is the departure time of outbound truck j, $j = 1,\ldots,N$
FT_j is the first cargo arrival time in the consolidation area for outbound truck j, $j = 1,\ldots,N$

LT_j is the last cargo arrival time in the consolidation area for outbound truck j, j = 1,…,N

Objective function:

$$\text{Minimize } \alpha\,(\bar{U} + \bar{V}) + \beta(\bar{WT}) \tag{1}$$

where

$\bar{U} = \frac{\sum_{j=1}^{N} Uj}{N}$, j = 1,…,N
$\bar{V} = \frac{\sum_{j=1}^{N} Vj}{N}$, j = 1,…,N
$\bar{WT} = \frac{\sum_{j=1}^{N} WTj}{N}$, j = 1,…,N
U_j = max {0, $Pdt_j - Dt_j$}, j = 1,…,N
U_j is the earliness of outbound truck j
V_j = max {0, $Dt_j - Pdt_j$}, j = 1,…,N
V_j is the tardiness of outbound truck j
$WT_j = LT_j - FT_j$, j = 1,…,N
WT_j is the longest waiting time span for recombination task j, which lasts from the first to the last arrival of related cargo in the consolidation area.

For the convenience of formulation, we introduce two dummy trucks for the unloading and loading area. These are, respectively, inbound trucks 0 and M + 1, outbound trucks 0 and N + 1. The processing time required for each inbound and outbound dummy truck is 0. The characteristics of these trucks are as follows:

$$y_{00} = ;y_{M+1M+1} = 1$$

$$St_0 = 0$$

$$Y_{00} = 1;\ Y_{N+1N+1} = 1$$

$$\sum_{s=1}^{K} x_{0s} = K;\ \sum_{s=1}^{L} X_{0s} = L$$

These constraints restrict both dummy inbound truck 0 and outbound truck 0 to be the first truck at the inbound and outbound bays.

$$\sum_{r=1}^{M} x_{rM+1} = K;\ \sum_{r=1}^{N} X_{rN+1} = L$$

These constraints restrict both dummy inbound truck M + 1 and outbound truck N + 1 to be the last truck at the inbound and outbound bays.

Constraints:

$$\sum_{r=1}^{M} y_{ir} = 1, \quad i = 1, \cdots, M + 1 \tag{2}$$

$$\sum_{i=1}^{M} y_{ir} = 1, \quad r = 1, \cdots, M + 1 \tag{3}$$

$$\sum_{r=1}^{N} Y_{ir} = 1, \quad i = 1, \cdots, N + 1 \tag{4}$$

$$\sum_{i=1}^{N} Y_{ir} = 1, \quad r = 1, \cdots, N + 1 \tag{5}$$

$$\sum_{r=1}^{s-1} x_{rs} = 1, \quad s = K + 1, \quad K + 2 \cdots M \tag{6}$$

$$\sum_{r=1}^{s-1} X_{rs} = 1, \quad s = L + 1, \quad L + 2 \cdots N \tag{7}$$

$$\sum_{s=r+1}^{M+1} x_{rs} = 1, \quad r = 1, \cdots, M \tag{8}$$

$$\sum_{s=r+1}^{N+1} X_{rs} = 1, \quad r = 1, \cdots, N \tag{9}$$

$$\sum_{r=s}^{M+1} x_{rs} = 0, \quad s = 0, \cdots, M + 1 \tag{10}$$

$$\sum_{r=s}^{N+1} X_{rs} = 0, \quad s = 0, \cdots, N + 1 \tag{11}$$

$$x_{0s} + x_{0r} + x_{rs} \le 2, \quad r < sr, \quad s = 1, \cdots, M \tag{12}$$

$$x_{sM+1} + x_{rM+1} + x_{rs} \le 2, \quad r < sr, \quad s = 1, \cdots, M \tag{13}$$

$$X_{0s} + X_{0r} + X_{rs} \le 2, \quad r < sr, \quad s = 1, \cdots, N \tag{14}$$

$$X_{sN+1} + x_{rN+1} + x_{rs} \le 2, \quad r < sr, \quad s = 1, \cdots, N \tag{15}$$

$$\mathrm{St}_i + \mathrm{G}(2 - y_{ir} - y_{jm}) \ge \mathrm{St}_j, \quad r > mi, r, j, m = 1, \cdots, M \tag{16}$$

$$St_i - St_j \geqslant PI_j - G(3 - y_{ir} - y_{jm} - x_{mr}),\ \ r > mi,\ r,\ j,\ m = 1,\ \ldots, M \tag{17}$$

$$FT_j \leqslant St_i + PI_i,\ \ V_{ij} = 1,\ \ i = 1,\ \ldots, M\ j = 1,\ \ldots, N \tag{18}$$

$$LT_j \geqslant St_i + PI_i,\ \ V_{ij} = 1,\ \ i = 1,\ \ldots, M\ j = 1,\ \ldots, N \tag{19}$$

$$Dt_j \geqslant LT_j + PO_j,\ \ j = 1,\ \ldots, N \tag{20}$$

$$Dt_i + G(2 - Y_{ir} - Y_{jm}) \geqslant Dt_j \tag{21}$$

r > m i,r = 1,…, N + 1; j,m = 0, 1,…, N

$$Dt_i - Dt_j \geqslant PO_j - G(3 - Y_{ir} - Y_{jm} - X_{mr}) \tag{22}$$

r > m i,r = 1,…, N + 1; j,m = 0, 1,…, N

Constraints 2 and 3 ensure that each inbound truck's precedence is unique. Constraints 4 and 5 ensure that each outbound truck's precedence is unique. Constraint 6 ensures that each non-dummy inbound truck has exactly one preceding truck (exclude any dummy trucks). Constraint 7 guarantees that each non-dummy outbound truck has exactly one preceding truck (exclude any dummy trucks). Constraint 8 ensures that each non-dummy inbound truck has exactly one succeeding truck (possibly a dummy truck). Constraint 9 ensures that each non-dummy outbound truck has exactly one succeeding truck (possibly a dummy truck). Constraint 10 restricts the inbound truck's precedence at the inbound bay so that it is consistent with its precedence in the task pool. Constraint 11 restricts the outbound truck's precedence at the outbound bay so that it is consistent with its precedence in the task pool. Constraint 12 specifies that if inbound trucks that ranked in the r^{th} and s^{th} place both immediately follow dummy inbound truck 0, they must be at different inbound bays. Constraint 13 specifies that if inbound trucks that ranked in the r^{th} and s^{th} place are both immediately followed by dummy inbound truck M + 1, they must be at different inbound bays. Constraint 14 specifies that if outbound trucks that ranked in the r^{th} and s^{th} place both immediately follow dummy outbound truck 0, they must be at different outbound bays. Constraint 15 specifies that if inbound trucks that ranked in the r^{th} and s^{th} place are both immediately followed by dummy outbound truck N + 1, they must be at different outbound bays. Constraint 16 specifies that if inbound truck j is ranked before inbound truck i, then the processing start time for inbound truck j also precedes the processing start time for inbound truck i. Constraint 17 ensures that if the processing of inbound truck j precedes the processing of inbound truck j, there must be enough time between them for the processing of inbound truck j to be completed. Constraint 18 specifies the first cargo arrival time for outbound truck j, whilst constraint 19 specifies its last cargo arrival time. Constraint 20 ensures that there is enough time for the last cargo to be loaded onto outbound truck j before its departure. Constraint 21 specifies that if outbound truck j is ranked before inbound truck i, then the departure time of outbound truck j is also before the departure time of outbound truck i. Constraint 22 ensures that if the processing of outbound truck j precedes the processing of outbound truck j, there will be enough time between them for the processing of outbound truck j to be completed.

4. Comparative analysis

4.1. Case design

Our experimental case is based upon an actual E-commerce company's distribution center. Every day, around 200 outbound trucks depart for local distribution. The departure time of the outbound trucks is concentrated between 12:00 and 1:00 pm and 6:00 and 7:00 pm. Outside of this it depends on specific customer requirements. There are 11 bays for shipping goods. For the inbound trucks the average unloading time is around 1 h and for the outbound trucks the average loading time is around half an hour. According to our model assumptions, only temporary storage is allowed in the distribution center. So, if *n* number of inbound trucks have arrived at the distribution center yard, around 2 * n number of outbound trucks will depart in that wave for local distribution.

4.2. Experiments and results

Test data was generated by specifying five parameters: the number of inbound bays, the number of outbound bays, the number of inbound trucks, the number of outbound trucks, the due time of outbound trucks. First of all, we generated the processing time for inbound trucks, which has the mean value of 0.5 h, and the processing time for outbound trucks, which has a mean value of 1 h. As a second step, we generated the due time of outbound trucks within a specified time horizon. After this, because of the uncertainty of customer orders, the value representing the relationship between the inbound truck and the outbound truck (V_{ij}) was generated randomly. As shown in Table 2, the maximum calculated time was 109,623.96 s for a specific data set (2 inbound bays − 2 outbound bays − 5 inbound trucks − 8 outbound trucks − 3 h for sorting with α equal to β). To assess the time cost for the experiment, we minimized the data so that it was in approximately equal proportion to the real practice case. And 126 groups of test results are generated.

As mentioned in the real case, every day, around 200 trucks depart from the distribution center, which has 11 outbound bays, and its working hour is around 10 h. We set 2 inbound bays-2 outbound bays-4 inbound trucks – 8 outbound trucks – 2 h for sorting as the basic experiment group. The parameter of inbound bay represents the inbound operation processing resource (include the unloading door, staging storage space, operation equipment, and human labor), while the outbound bay represents the outbound operation processing resource. Because of the computation time cost, we cannot simulate full-scale warehousing operation in the experiment. Corresponding to around 200 outbound trucks departing from the distribution center every day, in reality, we set 8 trucks will be sent out in each experiment group. And the number of outbound trucks can represent the number of operation tasks in the distribution center. In the basic experimental group, we reduced the operation resources and operation time in proportion to the number of tasks to be processed.

The computational environment was an HP Compaq PC with Intel® Core™ i7 CPU @ 3.40 GHz, and 16 GB RAM. The program was coded and solved by the integer programming solver ILOG CPLEX.

4.3. Analysis of the relationship between punctuality and synchronization

Fig. 4 shows the time results for the control group. The data set here was 2-2-4-8-3 (inbound bays – outbound bays – inbound trucks – outbound trucks – due time). $\bar{U} + \bar{V}$ is the mean of the lack of punctuality for the outbound trucks. $\bar{WT}$ represents the mean waiting time for the recombination tasks. The recombination tasks are correlated with the outbound trucks. Here are some specific observations regarding the results shown in Fig. 4:

(1) If ignoring the storage cost and only consider the penalty for lack of punctuality, the mean of the waiting time for recombination tasks $\bar{WT}$ is much longer, even if the punctuality performance is optimized.
(2) If the proportion of the storage cost increases a little bit in the objective function, the synchronization for the recombination tasks improves remarkably. Depending on the result, the value of $\bar{WT}$ decreases to as low as 82.56%, whilst keeping the value of $\bar{U} + \bar{V}$ steady.
(3) While the storage cost keeps increasing, both the degree of punctuality and the degree of synchronization stay the same until the unit storage cost reaches more than double the unit penalty for lack of punctuality. Depending on the result, when the unit storage cost is five times the unit penalty for lack of punctuality, the value of $\bar{WT}$ decreases by only 4.50% compared with the previous stage's value, whilst the value of $\bar{U} + \bar{V}$ increases by 22.82% (As shown in Fig. 5).
(4) As shown in Fig. 6. If ignoring the lack of punctuality cost and only consider the storage cost, the degree of synchronization is not improved. However, the average lack of punctuality time increases by 95% over the previous stage.

4.4. Sensitive analysis

4.4.1. Punctuality sensitive analysis

It can be seen from Fig. 7 that changes to the time constraint have the greatest influence on punctuality. When the due time is one hour ahead and the storage cost is low, the average time value for lack of punctuality reaches about twice that of the control group (group 2-2-4-8-3). This effect expands as the cost of asynchrony grows.

Fig. 5 also shows that, when the number of outbound trucks is increased, if the unit storage cost β is low, the impact on punctuality is small. However, as the value of β increases to a specific value (five times the penalty for lack of punctuality α in this case), the impact expands rapidly and the average lack of punctuality time increases explosively to double the value of the control group. Other elements, such as the number of inbound bays and the number of outbound bays, have a much smaller impact on the lack of punctuality, no matter how much the unit storage cost β changes.

4.4.2. Synchronization sensitive analysis

Fig. 8 indicates that the degree of synchronization is sensitive to the variables of due time, the number of inbound bays, and the number of outbound trucks. The number of outbound bays, however, has little effect on the degree of synchronization.

When time resources are tight (one unit is decreased in the experimental group) and the storage cost is low, the average waiting time for recombination tasks is about twice as much as the control group. Even if the storage cost is increasing, the value of $\bar{WT}$ is still above 1.5 times that of the control group.

When the inbound operation resource changes (an inbound bay is added in this experiment), the average waiting time due to operation asynchrony is reduced to close to zero and even the storage cost is low in the objective function. As the cost of warehousing increases, the value of $\bar{WT}$ becomes 0, which means perfect synchronization of all orders has been achieved.

If the number of outbound trucks increases, the degree of operation synchronization is affected if the storage cost is low. However, as the cost of being out-of-sync increases, the operation synchronization gets better.

4.4.3. Cost sensitive analysis

From Fig. 9 the sensitivity of total cost is similar to the sensitivity of synchronization. Tighter time makes the increasing of total cost. This influence continues regardless of how the asynchrony cost and lack of punctuality penalty changes. Flexible inbound operational resources lead to a lower total cost and, because all orders have to be approximate to be perfectly synchronized, the total cost keeps decreasing as the storage cost increases. More operational orders lead to a higher total cost too, but this influence is reduced when the asynchrony cost increases. A variable number of outbound bays, however, has a weak impact on total cost.

4.5. Management implications

According to the results of the control group and the sensitivity analysis, we can make the following recommendations for practice:

Zero warehouse costs are not possible in a real-world case, so we should not only consider the punctuality of orders when we optimize operation scheduling in distribution centers, otherwise the waste of storage space, labor and equipment resources will be enormous due to asynchronous operations. In our research, by considering the cost of asynchrony, the holding time of order at the temporary storage space can be dramatically decreased (95% in this paper). It means that goods are quickly transferred from inbound truck to the outbound truck in the distribution center. The resources related to the order picking operation also can be fast released to the next order picking task. The application of the synchronization mechanism greatly improved the efficiency of the distribution center.

When asynchrony cost is added to the objective function for optimizing scheduling, the cost ratio remains low and the degree of operation synchronization in the distribution center is greatly improved, which leads to much more effective operations.

This result is very significant when dealing with a growing number of E-commerce orders. It is not feasible for the logistics providers to keep expanding their distribution center's capacity to catch the fast-growing e-commerce orders. And his is also especially the case for holidays such as bank holidays when the number of orders can grow explosively and distribution centers can run out of capacity. If the new optimization strategy proposed in the practice case is adopted, the required distribution center space, human resources, and other equipment will be greatly reduced while dealing with the same number of orders. And those released resources become elastic order processing capacity in distribution center to deal with the additional growth orders.

Distribution center operation synchronization can be better realized by either increasing the number of inbound bays, adding labor and equipment to inbound operations, or improving the inbound operation's efficiency. It can be seen from Fig. 9 that, although the storage costs rise if you increase the inbound operation capacity, the total cost is decreased and punctuality is also improved.

5. Conclusions and future research

In this work we have studied an important problem for distribution centers which is the elimination of temporary inventory to ensure efficient transhipment operations and save cost. To meet such requirements operation synchronization is needed, as it is the most effective and direct way to keep low-level inventory. This paper has put forward new insights regarding distribution center operation scheduling by giving a specific measurement index for the degree of synchronization. In order to test our model, input data was collected from a real E-commerce distribution center and the size of the data was proportionally reduced to balance the CPLEX calculated time cost. The objective was to minimize the total cost of the lack of punctuality penalty and the storage costs due to asynchronous operation. Our observations were based on 126 groups of test results.

Based on the data from the experimental control group, if only considering the penalty for lack of punctuality, it is hard to guarantee synchronization. However, if considering the cost of storage due to asynchrony in the optimization model, even though this cost makes up a very small part of the total objective, the degree of operation synchronization can be greatly improved. Furthermore, when the storage cost is within a certain range, the punctuality is not affected. If warehousing costs rise to a high enough level (five times the penalty for lack of punctuality in this set of experiments), punctuality does decrease slightly, but it then remains stable until the ratio of the penalty for lack of punctuality has reduced to zero. In general, distribution center operation synchronization can not only decrease inventory level significantly by limiting the order waiting time in the combination area, it can also ensure the punctuality as well, as long as the penalty ratio for lack of punctuality and asynchrony is reasonable. According to the sensitivity analysis results, expanding a distribution center's inbound operation capacity is the most efficient way to realize better operation synchronization and control the total cost.

The distribution center operation synchronization problem discussed here has an important feature to bear in mind: our study case was a specific distribution center where all the inbound and outbound trucks were assumed to be parked in the yard at the outset. However, in future work, studies running comparisons across a range of different practice cases need to be undertaken. Furthermore, the model could be extended by matching up with the suppliers' pace of synchronization. We adopted CPLEX in this study to generate optimal results. However, for practical applications, heuristics or other efficient algorithms will be required [59]. In addition, it is worth considering whether other, new methodologies, such as auctioning, might offer more effective ways of solving the distribution center operation synchronization problem than modeling.

Appendix A. Figures and Tables

See Figs. 1–9.

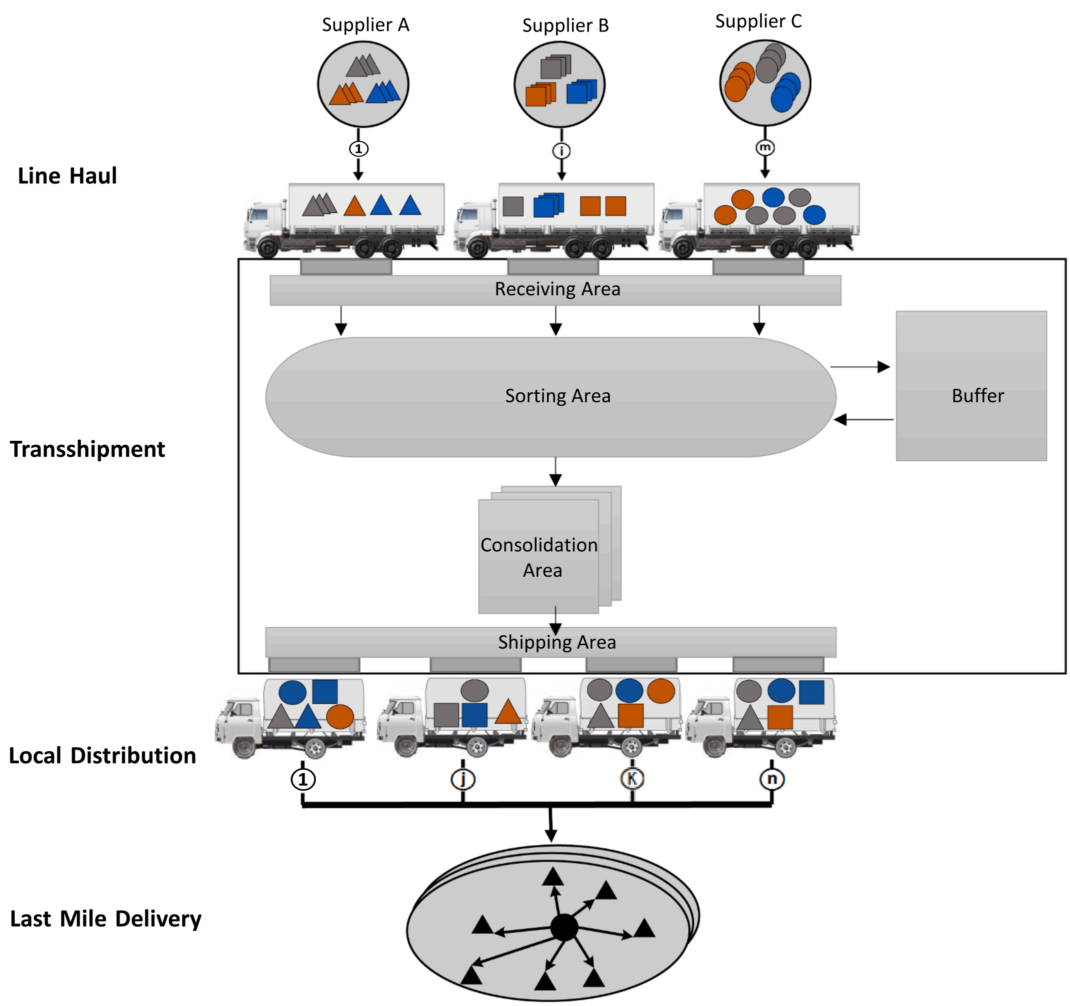

Fig. 1. E-commerce Logistics Service Network.

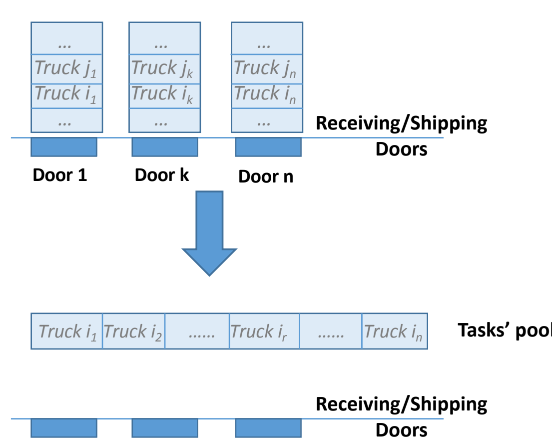

Fig. 2. Comparison of Li and Lim's scheduling model and the task pool scheduling model.

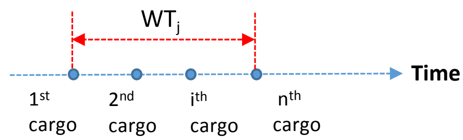

Fig. 3. Measure for synchronization.

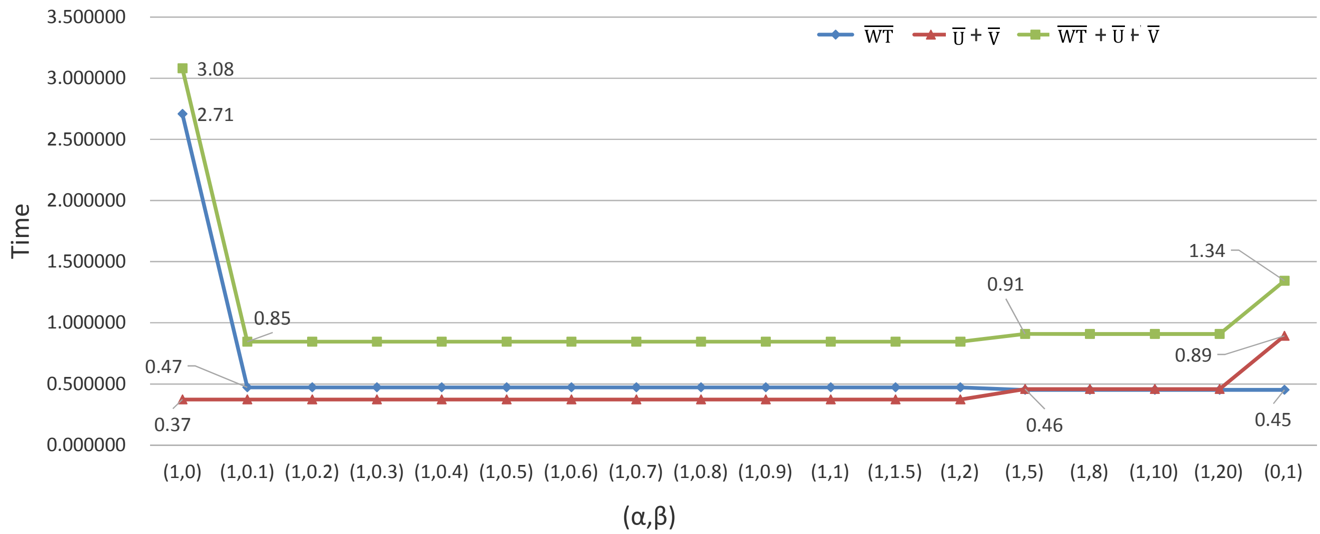

Fig. 4. Relationship between punctuality and synchronization.

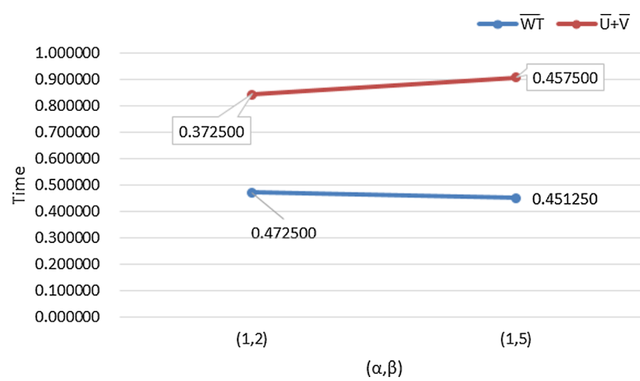

Fig. 5. The impact of continuously increasing unit storage cost.

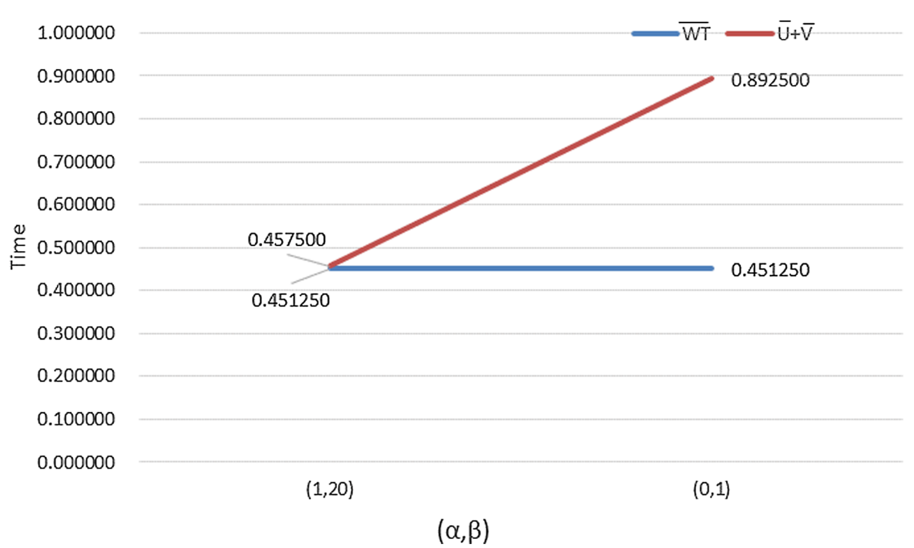

Fig. 6. The impact of ignoring the punctuality penalty.

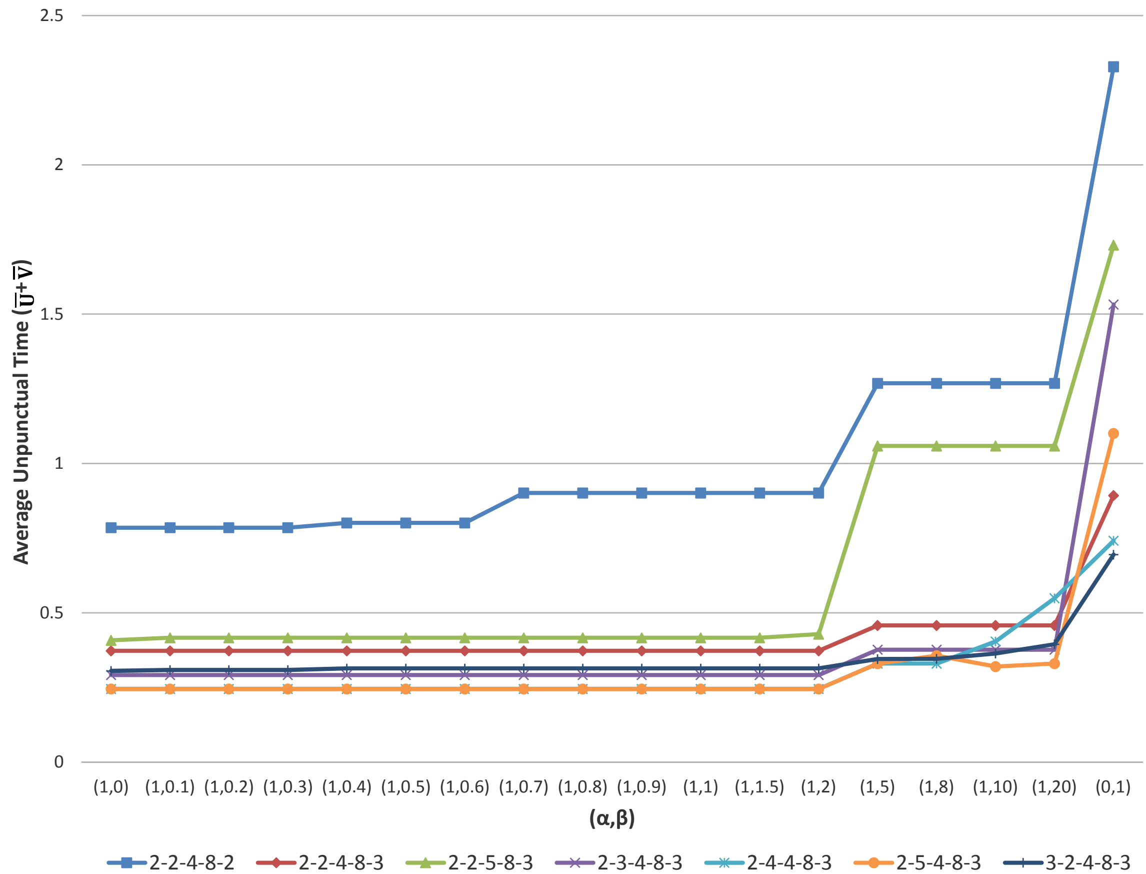

Fig. 7. Sensitivity of punctuality.

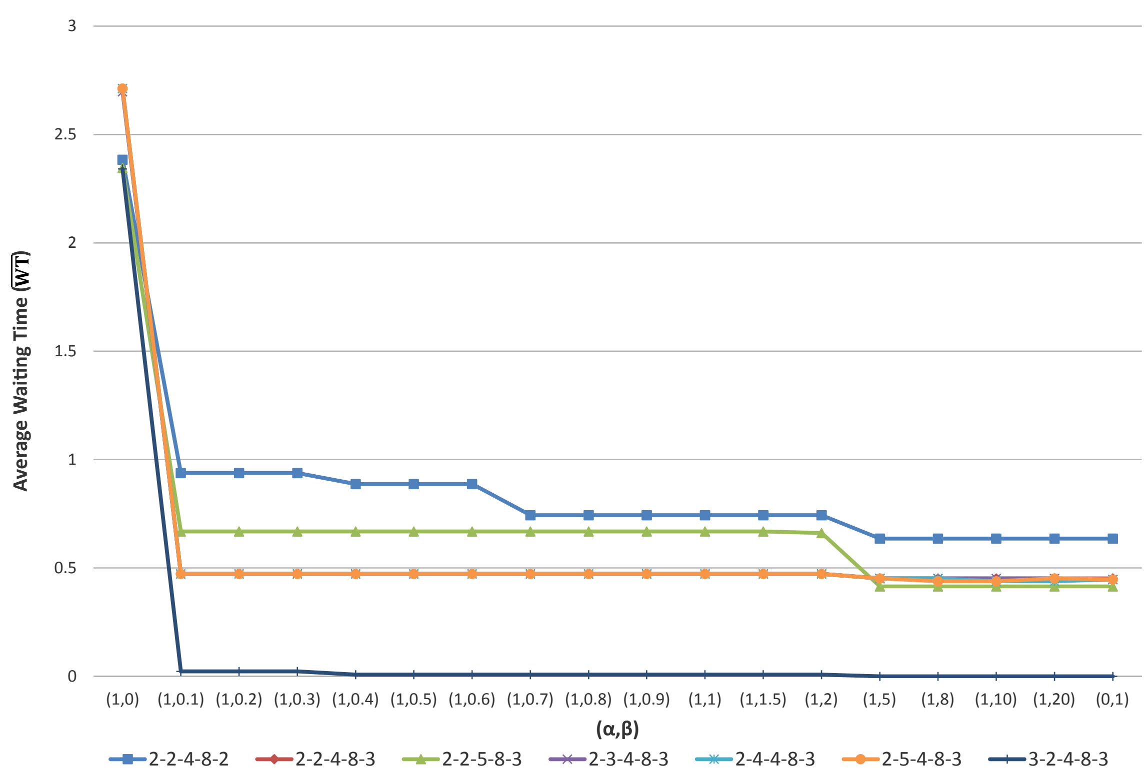

Fig. 8. Sensitivity of synchronization.

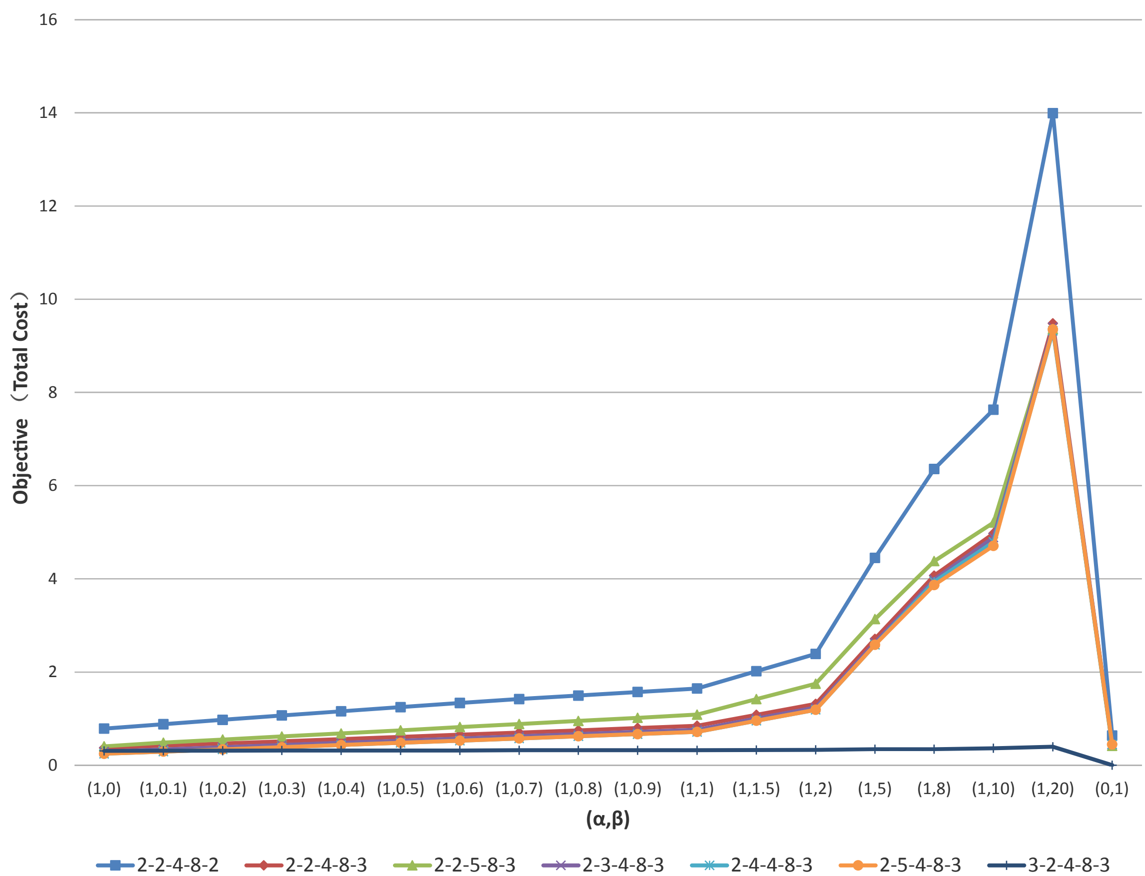

Fig. 9. Sensitivity of total cost.

See Tables 1–3.

Table 1
Literature review for models of the distribution center scheduling problem.

Sorting Mode	Manual	[51,52,26,14,35,35,43,19,23,38,37,42,25,45,57,11,46]
	Automatic	[6,41,56,20,29,38,37,39,47]
No. of Receiving /Shipping Doors	Single Receiving /Shipping Door	[2,28,56,20,44,7,4,25,47,53,1,5]
	Multiple Receiving /Shipping Doors	[51,52,26,14,31,6,35,35,43,48,19,41,12,21,23,29,38,37,38,37,42,15,3,39,45,57,11,46,16]
Storage Principle	Zero Inventory	[26,35,35,43,2,28,48,19,33,56,20,21,29,42,44,7,4,25,45,53,57,11,1,46,16]
	Allowing Temporary Storage	[51,52,31,6,41,12,38,37,38,37,15,3,39,47]
Outbound Truck Departure Principle	When All Relevant Orders Are Loaded	[51,52,31,6,43,2,28,48,41,56,12,20,21,29,38,37,38,37,44,7,15,3,4,25,39,47,57,46]
	At Fixed Times	[35,35,42,1,16]

Table 2
Experimental time for each data set *Unit: Time(s)*.

(α,β)	Inbound bays-Outbound bays-Inbound Trucks-Outbound Trucks-Due Time						
	2–2-4–8-2	*2–2-4–8-3*	*2–2-5–8-3*	*2–3-4–8-3*	*2–4-4–8-3*	*2–5-4–8-3*	*3–2-4–8-3*
(1,0)	12563.62	562.12	623.51	8607.5	22822.7	25302.21	239.98
(1,0.1)	158.08	1170.23	4053.47	15609.69	26212.3	15952.29	304.92
(1,0.2)	17,523	2051.4	11928.62	506.93	21161.85	22.09	277.71
(1,0.3)	9802.85	3908.17	20830.02	30508.76	23271.28	29818.5	304.95
(1,0.4)	168.28	6105.47	35743.28	21.22	4.49	2.89	301.44
(1,0.5)	18838.65	8381.15	50873.83	21649.65	35517.45	2037.75	342.84
(1,0.6)	11971.49	11050.22	65439.96	6657.78	2106.48	5.94	310.44
(1,0.7)	22354.65	12410.72	2201.6	34018.06	4.35	4.6	473.03
(1,0.8)	18638.35	12041.01	1892.73	8163.98	5685.81	16273.42	342.19
(1,0.9)	11971.49	16616.18	82750.5	10.67	4.04	3.23	329.69
(1,1)	22180.57	9805.6	109623.96	7799	3.98	2.31	280.91
(1,1.5)	7035.88	5051.09	30311.7	54812.81	25481.31	75.13	284.36
(1,2)	44699.3	2286.72	3642.25	73957.44	140.14	3257.94	316.29
(1,5)	47010.76	10848.89	1719.61	26.1	5.72	4.13	773.61
(1,8)	2966.86	2621.72	844.09	32.68	5.69	4.09	362.44
(1,10)	302.86	141.07	1494.61	33.21	2.32	2.98	455.23
(1,20)	47.08	3840.5	2901.26	26.72	1733.86	3.34	762.21
(0,1)	0.58	0.26	0.77	0.26	0.26	0.2	0.25

Table 3
The experiment desgin.

Parameters	Levels			
inbound bay	2	3		
outbound bay	2	3	4	5
inbound truck	4	5		
due time	2	3		

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