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An Integrated k-Means Clustering and Bi-Objective Optimization Approach for External Trucks Scheduling in Container Terminals

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Abstract. This paper introduces an approach for optimal scheduling of external trucks in container terminals. The proposed approach integrates the k-means clustering algorithm with a bi-objective optimization model. The k-means clustering algorithm matches the export and import containers into tuples, reducing the number of empty trips. The optimization model objectives are: minimizing the deviation from the trucking companies' preferred arrival times and minimizing the total truck turnaround times, while considering several essential aspects, such as yard resources capacity, congestion level, and trucking companies' preferences. The results depict that the proposed approach reduces the total number of required trips by 31.58% and provides the decision-makers with a tradeoff between the total truck turnaround time and the deviation from the trucking companies' preferred pickup time window.

Keywords. Truck appointment systems, cluster analysis, optimization, empty truck trip minimization, double moves

1. Introduction

Maritime transportation is the cornerstone of international trade and the economy as around 80% of the goods shipped worldwide are carried by vessels [1]. The tremendous growth in the containerized trade motivated the academic community to pay considerable attention to the operational planning of Container Terminals (CTs). As the Trucking Companies (TCs) are dealing with a large number of containers, that increases the probability that many trucks may reach the terminal gates during the same Time Window (TW). In addition, the fluctuation of the arrival patterns can negatively affect the terminal's performance, causing several problems such as long truck turnaround time, lower utilization of the terminals' resources, and increased truck emissions.

The emergence of such arrival peaks can also cause congestion problems at the terminal gates, affecting the terminal's resources, and the surrounding facilities'

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performance. Therefore, to control the arrivals of external trucks to the CTs, some container terminals implemented Truck Appointment Systems (TAS) where the truckers can book their preferred arrival TW. Although the application of typical TAS can control the quota of the trucks that visit the CTs in each time window, it partially solves the problem as a large portion of the external trucks visits the CTs to drop-off or pick-up only one container (i.e. single cycle). In contrast, each truck can carry at most two containers per trip depending on whether it is 20 ft or 40 ft. Therefore, when a truck visits the terminal to drop off one or two export containers, it can share the return trip with other companies to pick up their import containers (i.e., double-cycle).

In contrast, each truck can carry at most two containers per trip, depending on whether it is 20 ft or 40 ft. Therefore, when a truck visits the terminal to drop off one or two export containers, it can share the return trip with other companies to pick up their import containers (i.e., double-cycle).

Figure 1 shows the difference between single and double cycles. Truck 1 enters the terminal gate carrying only one export container, which is delivered to the corresponding yard block YB 2, then it leaves the terminal empty heading back to its origin point (single cycle). On the other hand, truck 2 represents a double cycle in which two export containers are dropped in specific YBs. The first container is dispatched to YB 1, and the truck continues to YB 3 to drop the second container. Then, instead of leaving the CT empty, it picked up two import containers from YB 4 and YB 5, respectively. The larger number of empty trips the larger the rates of fuel consumption and, consequently large amounts of emissions. Therefore, CTs need to utilize the maximum physical capacity of each truck to minimize the total number of required trips.

In this regard, this paper proposes an integrated clustering optimization-based TAS to manage the external trucks' arrival at the container terminal. The proposed approach consists of two main steps: (1) Using the daily data of target containers, K-means clustering is used to create subgroups of export and import containers separately in the form of [exp1, exp2] and [imp1, imp2]. The resulting subgroups are matched together based on prespecified features to produce a set of complete tuples from export and import containers (i.e., ([exp1, exp2], [imp1, imp2])). (2) A bi-objective optimization model is applied to the resulting set of tuples to minimize the total truck turnaround time (TTT), and the deviation from the preferred arrival times.

The remaining of the paper is organized as follows: section 2 includes the related work. Section 3 addresses the methodology of the proposed scheduling approach for external trucks at container terminals. The experimental work results and discussion are in section 4. While in section 5, the conclusions and directions for future work are illustrated.

2. Related Work

The planning of container terminals' hinterland operations has gained considerable attention in the last decades because of their direct impact on the congestion levels at container terminals and their negative effects on the different resources' utilization.

In this section, the articles that address the optimal scheduling of external trucks at container terminals are reviewed. Generally, truck appointment systems can be classified based on various criteria such as their types, whether a fixed or a flexible system, or based on their objectives (e.g., minimization of truck turnaround time, maximization of resources utilization).

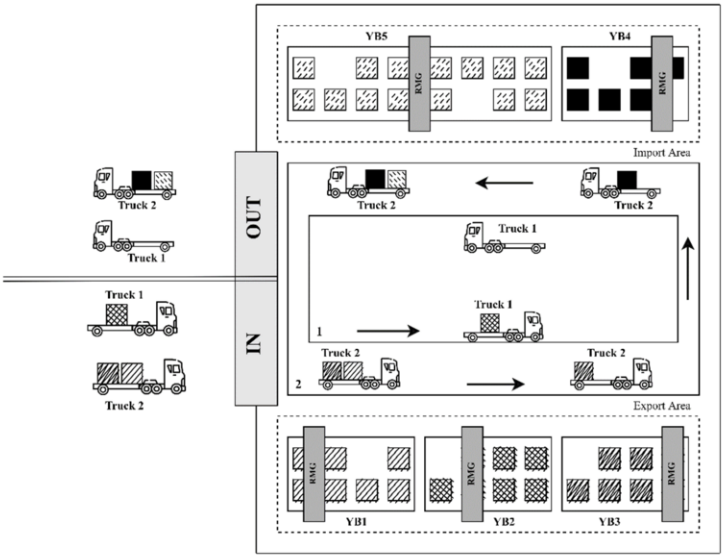

Figure 1. An example of single and double cycles

2.1. Fixed and Flexible Appointment Systems

In fixed appointment systems, the scheduling process is done by the terminal operators only, while the truckers are obliged to send their trucks to the terminal in the specified TW. Giuliano and O'Brien [2] studied the impact of implementing a mandatory TAS at two different container terminals. Although such TAS can control the external trucks' arrival patterns at the terminal gates, it increases the inconvenience of the trucking companies as sometimes the appointments assigned to them contradict with their delivery schedules to their customers.

In contrast, the scheduling process in the flexible TAS is conducted through a collaboration between the truckers and the terminal operators, where the TCs can select their preferred arrival time based on the appointments offered by the terminal. Phan and Kim [3] proposed a mathematical formulation for a collaborative TAS to minimize the arrival cost through each time window. A collaborative scheduling model to maximize the profit and lessen the harmful emissions is proposed by Schulte et al. [4]. In comparison, Azab et al. [5] combined discrete event simulation with a mixed integer programming model to minimize the total cost and increase the TCs' convenience.

2.2. Based on the Objectives of the Appointment System

Many authors discussed the external trucks scheduling problem with various objectives such as minimizing the turnaround, cost, waiting time and truck emissions, or maximizing resources utilization.

In order to minimize the truck turnaround time and terminals' congestion, the determination of the optimal number of appointments to be offered in each time window was proposed by Zehendner and Feillet [6], and Shiri and Huynh [7]. In contrast, Azab et al. [8] and Ramirez et al. [9] were concerned with minimizing the number of required containers' relocations. Furthermore, Phan and Kim [10] smoothed the arrival peaks of the external trucks along with reducing the inconvenience of the trucking companies. The minimization of the external and internal trucks waiting time was introduced by Zhang et al. [11]. To find the optimal schedules for each truck, Do et al. [12] proposed an approach that minimizes truck emissions. A mixed integer nonlinear program is developed by Torkjazi et al. [13] to reduce the cost of hinterland operations. Based on the comprehensive review conducted by Abdelmagid et al. [14], the truck turnaround time is one of the most considered objectives, while minimizing truck emissions is one of the least considered objectives. However, to the best of the authors' knowledge, only one article by Caballini et al. [15] discussed the minimization of the number of empty trips and the truck turnaround time by integrating data mining and optimization techniques.

In this regard and in the era of environmental sustainability, this paper proposes an approach that integrates a k-means clustering algorithm with a bi-objective optimization model to minimize: (1) The number of required trucks to move a set of containers by minimizing the number of empty trips. (2) The trucking companies' inconvenience. (3) The total truck turnaround time.

3. The Proposed Methodology

This section introduces the methodological framework of the proposed external trucks scheduling approach. The proposed approach integrates data clustering analysis and optimization techniques to develop the optimum appointment schedules that minimize the number of empty trucks, truck turnaround time, and deviation from the TCs preferred pickup time. Firstly, the daily collected data is fed into a clustering algorithm to create distinct subgroups of export and import containers. Then, the resulting subgroups are matched together based on specific rules to form a set of tuples. Secondly, the resulting set of tuples, preferred arrival times, and the corresponding yard blocks information are processed in the optimization model to obtain the appointment schedules.

The proposed approach aims to minimize the number of empty trips, increasing the satisfaction of the trucking companies by reducing the gap between the assigned appointments and their preferred arrival times, and decrease the congestion at the terminals by reducing the turnaround time.

3.1. Step 1: K-means Clustering

The k-means clustering algorithm aims to maximize the number of double moves and consequently minimizes the total number of required trucks to move the same set of containers, decreasing fuel consumption and greenhouse gas emissions.

The clustering procedure follows three steps to create each tuple: (1) Creating subgroups of export containers [ex1, ex2]. (2) Creation of subgroups of import containers [im1, im2]. (3) Matching the export and import subgroups together based on specified criteria to form the final shape of tuples ([ex1, ex2] , [im1, im2]).

Based on the comprehensive survey conducted by Xu and Tian [16], there are several clustering algorithms based on partition, hierarchy, distribution, density, or grid.

In this study, the partitioning clustering algorithm (k-means) is used as it is relatively simple, and the number of clusters can be determined considering the minimization of the within-cluster squared error. The steps of the k-means clustering procedure are as follows: (1) selecting the number of clusters, (2) assigning each data point to a cluster randomly, (3) computing a new centroid for each cluster, (4) assessing the quality of each cluster, (5) repeating the steps with different numbers of clusters to construct the elbow plot. (6) selecting the appropriate number of clusters that minimize the within-cluster squared error. The clustering procedure is carried out considering multiple containers' attributes, some of them are general regardless the cycle of each container (export or import), while others are dedicated to each cycle separately.

General Attributes

- **Type:** defines the cycle of each container, whether it's an import or export.
- **Weight:** represents how much each container weighs. This feature is crucial for tuples formation as it bounds each truck' per trip. In the presented case, the total weight that each truck can carry is 30 tons.
- **Size:** reflects the size of each container related to whether it's 20ft or 40ft. This feature is one of the fundamental matching criteria while creating the export and import subgroups.
- **Agreement:** represents the trucking companies' willingness to share their trucks. This directly affects the number of empty trips. For instance, each container belonging to a trucking company that disagrees to carry containers for others will be moved in an empty trip.
- **Distance:** captures the travel distance between the yard blocks to drop or pickup each container.

Import Containers Attributes

- **Delivery location:** captures the final destination to which each import container needs to be delivered in the hinterland.
- **Clearance:** identifies whether the trucking company paid the customs clearance fees and finished the paperwork or not. The container cannot be moved from the terminal unless it fulfills this condition.
- **Yard block waiting time:** represents the period each import container has been waiting in the terminal.

Export Containers Attributes

- **Vessel departure time**: represents the departure time for each vessel corresponding to each export container.

The tuples are created in the light of the above attributes, and each tuple is assigned to a truck. The preferred pickup time for each tuck is defined based on the earliest vessel departure time of the export containers in each tuple.

3.2. Step 2: The Optimization Model

In this step, a bi-objectives optimization model is developed to assign each created tuple to a specific time window. However, according to the terminals' limited resources and productivity, sometimes the terminal operators can not satisfy all the TCs' arrival proposals. Therefore, the optimization model aims to minimize the gap between the trucking companies' assigned time window and the proposed pickup time window and to minimize the total turnaround time.

The proposed model adopted the mixed integer programming model developed by Caballini et al. [15]. In addition, there are several methods to solve multi-objective optimization models, such as goal programming, epsilon constraint method, and scalarization method. In this paper, the model was solved using the epsilon constraint method to develop a Pareto-front tradeoff between the two objectives. The proposed approach reflects the flexibility to be applied from both perspectives of the terminal operators and the trucking companies.

Model Sets and Parameters

- S: represents the set of time windows.
- N: the set of created tuples.
- A: the set of all terminal yard blocks.
- A_n: represents the sequence of yard block visited by a truck corresponding to tuple n where $n \in N$.
- u_n^a: defines the number of containers to be picked up or delivered related to tuple $n \in N$ in and yard block $a \in A_n$.
- g_n: the preferred pickup time window of each truck corresponding to tuple $n \in N$.
- α_n: represents the priority of each tuple $n \in N$. The value of this parameter changes according to whether it's a single cycle (1) or a double cycle (2).
- δ_{max}: the maximum permissible gap between the assigned time window and the preferred arrival time of each truck.
- β_s^a: the congestion level of each yard block $a \in A$ during each time window $s \in S$.
- ρ_s^a : the container handling resources productivity of s block $a \in A$ during time window $s \in S$.
- Q_s^a : the number of available moves during time window $s \in S$ at block $a \in A$.
- T_n^{IN} : the required travel time of a truck belongs to tuple $n \in N$ to reach the first container yard area.
- T_n^{OUT} : the required travel time of a truck belonging to tuple $n \in N$ to reach the gate after performing the final cycle in the tuple.
- $T_n^{a,a+1}$: the required travel time a truck belongs to tuple $n \in N$ has to spend to travel from one yard block $a \in A_n$ to the next yard block $a + 1 \in A_n$.

Decision Variables

- x_{ns}: binary variable represents whether to assign tuple $n \in N$ to time window $s \in S$ or not.
- δ_n: integer variable represents the gap between the assigned time window and the TC proposed pickup time of tuple $n \in N$.
- L_{ns}: continuous variable represents the turnaround time of a truck related to tuple $n \in N$ if it is assigned to time window $s \in S$.

Objective Functions

$$obj_1\text{: Min } \sum_{n \in N} \alpha_n \cdot \delta_n \tag{1}$$

$$obj_2\text{: Min } \sum_{n \in N} \sum_{s=1}^{S} L_{ns} \tag{2}$$

Constraints

$$\sum_{s=1}^{S} x_{ns} = 1 \qquad \forall n \in N \tag{3}$$

$$\sum_{s=1}^{S} s \cdot x_{ns} - g_n = \delta_n \qquad \forall n \in N \tag{4}$$

$$\delta_n \leq \delta_{max} \qquad \forall n \in N \tag{5}$$

$$\delta_n \geq -\delta_{max} \qquad \forall n \in N \qquad (6)$$

$$\left(t_N^{in} + \sum_{a \in A_n} \left(\frac{u_n^a \cdot 60}{\rho_s^a \cdot \beta_s^a} + t_n^{a,a+1}\right) + t_n^{out}\right) \cdot x_{ns} \leq L_{ns} \qquad \forall n \in N, \forall s \in S \qquad (7)$$

$$\sum_{n \in N, a \in A} u_n^a . x_{ns} \leq Q_s^a \qquad \forall\, a \in A,\ \ s \in S \qquad (8)$$

$$x_n^s \in (0,1) \qquad \forall n \in N, \forall s \in S \qquad (9)$$

$$\delta_n \geq 0 \qquad \forall n \in N \qquad (10)$$

$$L_n^s \geq 0 \qquad \forall n \in N, s \in S \qquad (11)$$

The first objective (1) aims to minimize the gap between the TAS scheduled time window and the TCs proposed arrival time window, while the second objective (2) aims to minimize the total turnaround time of the external trucks. Constraint (3) guarantee that each tuple is served only one time. Constraint (4) computes the deviation between the scheduled time window and the preferred pickup time. The maximum acceptable gap δ_{max} between the TCs proposed pickup time and the TAS scheduled time is defined by constraints (5) and (6). Constraint (7) computes the turnaround time if a truck belonging to tuple n is assigned to time window s. The number of available moves at each YB during each time window is bounded in constraint (8). Constraints (9), (10), and (11) defines the nature of the decision variables.

The proposed model is solved using the epsilon constraint method as follows: Step1: the problem is solved considering the first objective Eq. (1) only while subjected to constraints from (3) to (11) to define the lower bound value of the first objective (the starting point of the curve). Step 2: the problem is solved again considering the second objective Eq. (2) only while subjected to constraints from (3) to (11) to define the lower bound of the second objective (the end point of the curve). Step 3: the problem is solved considering only one objective and the other will act as inequality constraint subjected to different values to get the Pareto-front representation of the two objectives.

It is worth bearing in mind that the proposed approach can be applied from both perspectives of the container terminal and the trucking companies.

4. Results and Discussion

All the experiments have been carried out and the results were generated and analyzed using an Intel i7- 9750H CPU 2.6 GHz computer, and 16 GB of RAM. The k-means clustering algorithm was coded in R programming language and solved using the R-Studio software package. The optimization model was coded and solved using Gurobi-Python (version 9.5.1) optimization package.

A data set of 1000 containers was generated based on realistic assumptions. For instance, the number of export containers represents 30% of all containers, and the number of 20 ft containers represents 80% of all containers. Furthermore, the percentage of the trucking companies that agree to perform double cycles was 70% of all companies, and 70% of the containers fulfilled the customs clearance papers. In this experiment eight terminal blocks, eight time windows each of one hour, and five different destinations of the import containers were considered. The maximum allowed gap between the assigned time window and the preferred pickup time of the trucking companies (δ_{max}) was set to four.

In this section the results of the clustering analysis and the optimization phase are depicted separately to highlight the impact of each step.

4.1. Step 1: The k-means Clustering Algorithm Results

In the light of the previously mentioned procedure of the k-means clustering technique, the elbow plot is used to determine the number of clusters that minimizes the within cluster squared error. In Figure (2a) the relationship between the number of export containers' clusters and the value of the within clusters squared error is conducted. Based on Figure (2a), it is recommended to use a number of 17 clusters as it has a low value of the squared error, and the improvement obtained from increasing the number of clusters is worthless when compared to the increase in the computational effort. While the number of clusters selected for the import containers was 25 according to the elbow plot of the import containers Figure (2b). In this experiment, due to the customs clearance papers, only 782 containers were available to move.

Compared to the base case of a typical TAS, the proposed k-means clustering approach created 532 tuples to move the same number of containers reducing the number of required trucks by (31.91%).

4.2. Step 2: Optimization Model Results

The resulting tuples from the clustering analysis are considered as the inputs of the optimization model. The epsilon constraint method was used to develop a tradeoff between the deviation from the preferred arrival time and the total turnaround time. The Pareto-front (Figure 3) provides the decision-makers in the trucking companies and container terminals with multiple what-if scenarios between the values of the two objective functions. Figure 4 depicts an example of the number of scheduled appointments during each time window corresponding to the avg values of both objective functions (obj_1= 102, and obj_2= 30161).

In this case, the average turnaround time per truck was 56.67 min, and the maximum deviation (δ_{max}) from the preferred arrival time observed was two slots.

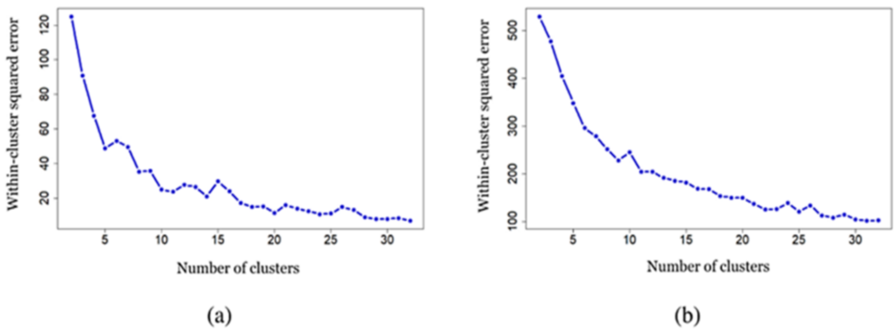

Figure 2. Elbow plot for export clusters (a), and elbow blot for import clusters (b)

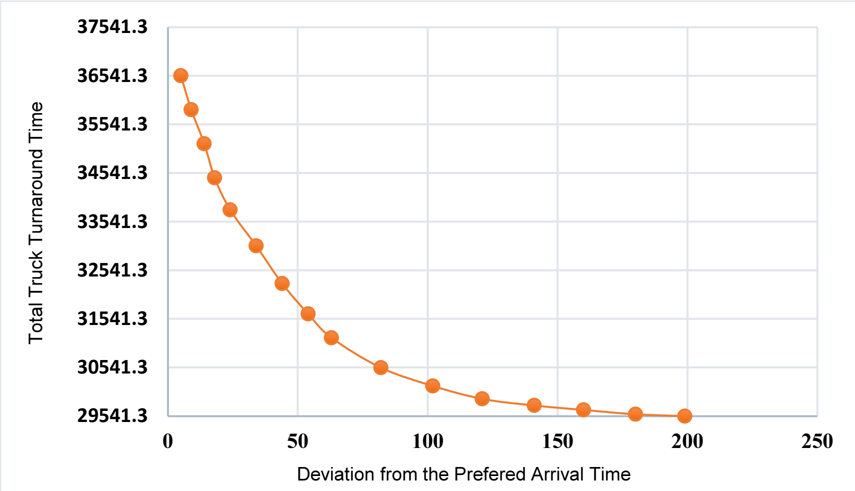

Figure 3. The Pareto Front between the two objectives

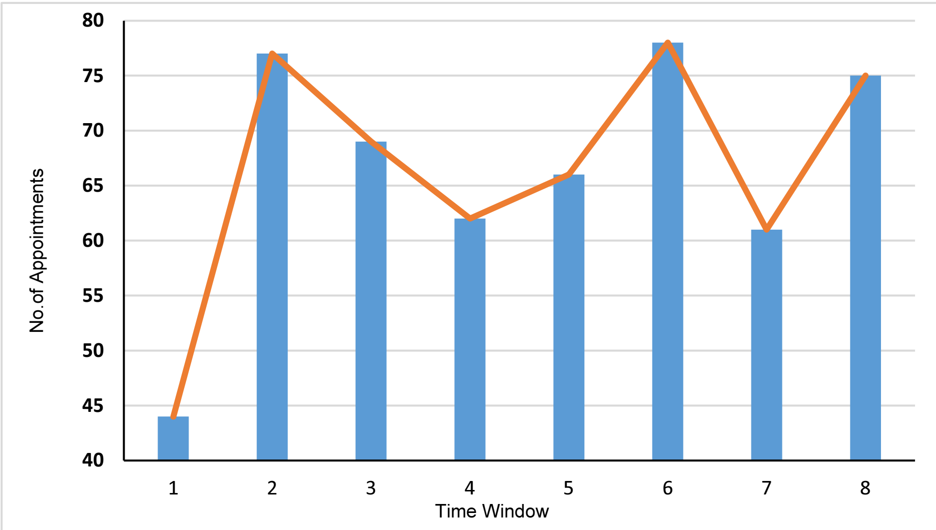

Figure 4. Appointments distribution among the eight time windows.

5. Conclusion

This article proposes a scheduling approach for external trucks in container terminals, which integrates data analysis and optimization represented by the k-means clustering algorithm and a bi-objective optimization model. The proposed clustering algorithm aims to reduce the number of empty trips by increasing the number of shared trips. While the optimization approach objectives are: (1) The minimization of the gap between the trucking companies' preferred pickup time window and consequently increasing the satisfaction of The truckers. (2) The minimization of the total turnaround time.

It is worth noting that, this approach can be applied from both perspectives of the trucking companies and terminal operators. In addition, the results obtained from the clustering analysis pointed out that, the number of required trucks was reduced by 31.91%. Furthermore, epsilon constraint method was used to provide the decision makers in both the container terminals and tucking companies with a trade-off between the deviation from the preferred arrival time proposed by the trucking companies and the total truck turnaround time.

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