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OPTIMIZATION ON COMBINED SCHEDULING OF TRACTOR AND TRAILER ROUTING PROBLEM CONSIDERING SYNCHRONIZED OPERATIONS

Qi Xu[1], Zuona Li[2], Lixin Shen[3,*], Zhan Bian[4], Lei Xing[1] and Zhihong Jin[1]

[1]College of Transportation Engineering
[3]College of Maritime Economics and Management
Dalian Maritime University
No. 1, Linghai Road, Dalian 116026, P. R. China
*Corresponding author: slx_1106@163.com

[2]Yunnan Science Research Institute of Communication & Transportation
No. 9, Shijia Lane, Tuodong Road, Kunming 650011, P. R. China

[4]College of Business Administration
Capital University of Economics and Business
No. 121, Zhangjialukou, Huaxiang, Fengtai District, Beijing 100070, P. R. China

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Abstract. *The tractor and trailer transport is such an advanced mode of transport that, according to the predetermined operation plan, the tractor drops a trailer at the loading/unloading node, and pulls another trailer to keep operating. The tractor and trailer transport has the unique characteristic of "synchronized operation by multi-machines". Based on the analysis of the characteristic, this paper proposed a combined scheduling model in the tractor and trailer transport under the cycle mode. A heuristic algorithm was proposed to solve the proposed problem. Numerical experiments were carried out to testify the effectiveness of the proposed mathematical model and algorithm. Sensitivity analysis on key parameters shows the effect of different scheduling rule and proportion of tractor-to-trailers on transport cost.*

Keywords: Tractor and trailer transport, Synchronized operation by multi-machines, Combined scheduling, Heuristic

1. **Introduction.** The tractor and trailer transport has been the main way of transportation in some developed countries. However, the tractor and trailer operation is still in its infancy in China, and gets the focused promotion by the Ministry of Transport. The operation flow of the tractor and trailer transport can be simplified as follows: according to the predetermined operation plan, a tractor decouples a trailer at the loading/unloading node, and couples another trailer to keep operating. Compared with other traditional transport mode, this mode has lower cost, higher efficiency, faster vehicle turnover, because the tractor does not have to wait at depots for loading/unloading cargos.

The Tractor and Trailer Routing Problem (TTRP) has attracted the attention of researchers both at home and abroad, and some research fruits have been achieved. Villegas et al. [1] made some research on the TTRP with single depot, and designed two algorithms GRASP/VND (Greedy Randomized Adaptive Search Procedure/Variable Neighbourhood Descent) and ELS (Evolutionary Local Search) to solve the problem. Then they added the enhancement mechanism (PR and EvPR, Path Relinking and Evolutionary PR), into the GRASP/VND algorithm, and got a better solution [2]. Zhang et al. [3] established a

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model based on the directed graph of the network with time windows, and designed the reactive Tabu search algorithm to solve the problem. Lin et al. [4] designed the simulated annealing algorithm to solve the TTRP with time window. Zhang et al. [5] applied a two-stage approximation approach to solving the dynamic planning problem for urban drayage operations. Hu et al. [6,7] established a priority relationship network for the consolidation/configuration tasks by introducing the virtual tasks; based on the network, a mix-integer planning model aiming at minimizing the total operation times was established and solved. Villegas et al. [8] applied a fast and efficient two-stage metaheuristic to solving the traditional TTRP problem and the corresponding problem relaxing the fleet constraints. Ulrich et al. [9] made some research on the derivative problem of the TTRP problem, considering the transfer between the tractor and trailer and constraints of the time window, and applied the hybrid heuristic to solving the problem. Li et al. [10] proposed the tractor and semitrailer routing problem with many-to-many demand considering carbon dioxide emissions, and applied a three-stage heuristic to solving the problem. Xue et al. [11,12] analyzed the local container drayage problem in which both the routes of the tractors and the operation time of the tractors were optimized. Manuel et al. [13] applied the branch and cut algorithm to solving the single tractor and trailer routing problem with satellite depots. Wang et al. [14] developed the self-adaptive bat algorithm for the TTRP. They designed five neighborhood search structures and the self-adaptive adjustment strategy to guarantee the characteristics of the diversity for all the particle swarms.

TTRP is the Pickup and Delivery Problem with Time Windows (PDPTW) in nature. Due to the characteristic of the "synchronized operation by multi-machines" of the TTRP, the solutions of the TTRP include not only the travelling routes of all the tractors, but also the decisions such as where and when the tractors and the trailers get separated, whether the trailers are moving together with containers, and whether the containers are full or empty. That means, the difficulty in solving the proposed problem is much higher than that of the ordinary PDPTW.

However, existing researches [1-4,8,9,14] mainly made researches on the TTRP about optimizing the route of the trucks without considering the scheduling decision of trailers. The other literature focused on the scheduling decision of tractors, considering that the number of trailers is unlimited. In summary, all of the existing researches cannot solve the scheduling decision problem with the characteristic of the "synchronized operation by multi-machines" fundamentally, which is the basic distinguishing characteristics of the TTRP with traditional PDPTW. Based on the analysis above, this paper will establish a combined scheduling model aiming at presenting scheduling plan for both tractors and trailers. Then, a heuristic will be designed to solve the problem, realize the visualization of the detailed operation steps for both tractors and trailers, and make the whole optimization results operational and efficient.

2. **Problem Modelling.**

2.1. **Problem description.** The objective of this paper is to optimize the combined scheduling plan of the TTRP considering the characteristic of "synchronized operation by multi-machines". The empty trailers can be shared in customer depot, but the maximum number of empty trailers idled in customer depots is predetermined. When the number of empty trailers idled is larger than the maximum value permitted, tractors must be scheduled to retrieve extra idled trailers at the customer depots. There are two kinds of tasks in the transport system, as illustrated in Table 1.

TABLE 1. Task description of tractors and trailers under the cycle mode

Task category	Index of task	Origin	Destination
Full container task	1	Customer depot	Customer depot
Empty container task	2	Customer depot/yard	Customer depot/yard

2.2. **Proposed model.**

2.2.1. *Assumptions of the model.*

(1) The travelling speeds for tractors are the same when moving without anything, empty loaded or full loaded;

(2) One tractor can only pull one trailer, and only one container can be put on one trailer;

(3) Only the FCL (Full Container Load) transport is considered in this paper; the trailer and the container cannot be separated during the transport process and all the container size is FEU;

(4) The loading/unloading times of containers at the customer depot are the same and predetermined, and the hanging/unhanging times of trailers are the same and predetermined;

(5) The traffic demand between customer depots is predetermined and the unit is FEU;

(6) All the tractors start at the yard and get back at yard at the end of the planning horizon;

(7) The empty trailers are to meet the demand at the customer depot, and only after that, can the empty trailers be used to meet the demands at other customer depots;

(8) If there is transport demand at the customer depot, the empty trailers staying there at the end of the previous planning horizon are to be used firstly to meet the demand;

(9) The empty trailers transferred from the full container tasks in the tth time window, can only be used to operate in the $t+1$th time window.

2.2.2. *Notations of the model.*

(1) Parameters

$G = \{V, D\}$: sets of the transport network. Therein, $V = \{0, 1, 2, \ldots, I\}$ is the set of all the nodes, 0 represents the yard, $1, 2, \ldots, I$ represent the customer depots, D is the set of distances among all the nodes;

C_1: the transport cost coefficient of tractors travelling without carrying anything;

C_2: the extra transport cost coefficient of tractors because of pulling trailers;

K: the number of tractors;

L: the number of trailers;

R: the number of tasks;

T: the time of the planning horizon;

M: maximum number of tasks that can be completed in the planning horizon by one tractor;

N: maximum number of tasks that can be completed in the planning horizon by one trailer;

$J(s)$: set of tasks which belongs to task category s, $s \in \{1, 2\}$;

Q_{ij}: transport demand from point i to point j;

D_{ij}: distance between point i and point j;

v: the travelling velocity of tractors;

t_0: starting time at the planning horizon;

t_1: loading/unloading time of container onto/off trailer;

t_2: hanging/unhanging times of trailers with/off tractor;
t_w: maximum waiting time of loaded trailer at customer depot;
$t_r(1)$: starting time of task r at the origin;
$t_r(2)$: finishing time of task r at the destination;
TW: length of the time windows;
MTW: number of the time windows;
$KG_i(t)$: number of idled empty trailers at node i at the beginning of the time window t, $t \in \{0, \ldots, MTW-1\}$;
$ZG_i(t)$: number of full trailers at node i at the beginning of the time window t, $t \in \{0, \ldots, MTW-1\}$;
$DGC_i(t)$: number of trailers to be transported at node i at the beginning of the time window t, $t \in \{0, \ldots, MTW-1\}$;
$GC_i(t)$: number of trailers at node i at the beginning of the time window t, $t \in \{0, \ldots, MTW-1\}$;
$ED_i(t)$: number of empty trailer requirements at node i at the beginning of the time window t, $t \in \{0, \ldots, MTW-1\}$;
CK_i: number of empty trailers staying at customer depot i at the end of the previous planning horizon;
PK_0: number of empty trailers staying at yard at the beginning of the planning horizon;
MGC_i: maximum number of trailers that can stay at customer depot i;
MKG_i: maximum number of idled empty trailers that can stay at customer depot i;

$$t_r^1(t) = \begin{cases} 1, & \text{if the beginning time of task } r \text{ is in the } t\text{th time window} \\ 0, & \text{otherwise} \end{cases},$$
$\forall r \in \{1, \ldots, R\}$, $t \in \{0, \ldots, MTW-1\}$;

$$t_r^2(t) = \begin{cases} 1, & \text{if the finishing time of task } r \text{ is in the } t\text{th time window} \\ 0, & \text{otherwise} \end{cases},$$
$\forall r \in \{1, \ldots, R\}$, $t \in \{0, \ldots, MTW-1\}$;

$$t_r^3(t) = \begin{cases} 1, & \text{if the finishing time of loading/unloading operation after} \\ & \text{task } r \text{ is in the } t\text{th time window} \\ 0, & \text{otherwise} \end{cases},$$
$\forall r \in \{1, \ldots, R\}$, $t \in \{0, \ldots, MTW-1\}$.

(2) Decision Variables

$$x_{rkm} = \begin{cases} 1, & \text{if task } r \text{ is completed by tractor } k, \text{ as the } m\text{th task of tractor } k \\ 0, & \text{otherwise} \end{cases},$$
$\forall r \in \{1, \ldots, R\}$, $k \in \{1, \ldots, K\}$, $m \in \{1, \ldots, M\}$;

$$y_{rln} = \begin{cases} 1, & \text{if task } r \text{ is completed by trailer } l \text{ as the } n\text{th task of trailer } l \\ 0, & \text{otherwise} \end{cases},$$
$\forall r \in \{1, \ldots, R\}$, $l \in \{1, \ldots, L\}$, $n \in \{1, \ldots, N\}$;

$$z_{ij}^r = \begin{cases} 1, & \text{task } r \text{ is from node } i \text{ to node } j \\ 0, & \text{otherwise} \end{cases},$$
$\forall i, j \in \{0, \ldots, I\}$, $r \in \{1, \ldots, R\}$;

$$\alpha_{ij}^k = \begin{cases} 1, & \text{if tractor } k \text{ travels from node } i \text{ to node } j \\ 0, & \text{otherwise} \end{cases},$$
$\forall i, j \in \{0, \ldots, I\}$, $k \in \{1, \ldots, K\}$.

2.2.3. *Mathematical model.* The objective of the model established in the paper is to minimize the total routing costs of the transport system, which can be illustrated as Equation (1).

$$\min Z = C_1 \cdot \sum_{k=1}^{K}\sum_{i=0}^{I}\sum_{j=0}^{I} D_{ij} \cdot \alpha_{ij}^{k} + C_2 \cdot \sum_{r=1}^{R}\sum_{i=0}^{I}\sum_{j=0}^{I} D_{ij} \cdot z_{ij}^{r} \tag{1}$$

The constraints in the operation system are concluded as follows.

$$\sum_{k=1}^{K}\sum_{m=1}^{M} x_{rkm} = 1,\ \forall r \in \{1,\dots,R\} \tag{2}$$

$$\sum_{l=1}^{L}\sum_{n=1}^{N} y_{rln} = 1,\ \forall r \in \{1,\dots,R\} \tag{3}$$

$$\sum_{i=0}^{I}\sum_{j=0}^{I} z_{ij}^{r} = 1,\ \forall r \in \{1,\dots,R\} \tag{4}$$

$$\sum_{r=1}^{R} x_{rk(m+1)} \le \sum_{r=1}^{R} x_{rkm},\ \forall k \in \{1,\dots,K\},\ m \in \{1,\dots,M-1\} \tag{5}$$

$$\sum_{r=1}^{R} y_{rl(n+1)} \le \sum_{r=1}^{R} x_{rln},\ \forall l \in \{1,\dots,L\},\ n \in \{1,\dots,N-1\} \tag{6}$$

$$\sum_{j=0}^{I}\sum_{k=1}^{K} \alpha_{ji}^{k} = \sum_{j=0}^{I}\sum_{k=1}^{K} \alpha_{ij}^{k},\ \forall i \in \{0,\dots,I\} \tag{7}$$

$$\sum_{l=1}^{L}\sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{i=0}^{I}\sum_{j=0}^{I} x_{rkm} \cdot y_{rln} \cdot z_{ij}^{r} = 1,\ \forall r \in \{1,\dots,R\} \tag{8}$$

$$\sum_{r\in J(1)} z_{ij}^{r} = Q_{ij},\ \forall i,j \in \{1,\dots,I\} \tag{9}$$

$$CK_i + \sum_{r\in J(1)}\sum_{j=1}^{I} z_{ji}^{r} + \sum_{r\in J(2)}\sum_{j=0}^{I} z_{ji}^{r} \ge \sum_{r\in J(1)}\sum_{j=1}^{I} z_{ij}^{r},\ \forall i \in \{1,\dots,I\} \tag{10}$$

$$\sum_{r_2=1}^{R}\sum_{r_1=1}^{R}\sum_{i=0}^{I}\sum_{j=0}^{I}\sum_{w=0}^{I} y_{r_1ln} \cdot z_{ij}^{r_1} \cdot y_{r_2l(n+1)} \cdot z_{jw}^{r_2} = 1,\ \forall l \in \{1,\dots,L\}, n \in \{1,\dots,N-1\} \tag{11}$$

$$\sum_{r_2\in J(2)}\sum_{i=1}^{I} y_{r_2l(n+1)} \cdot z_{0i}^{r_2} = \sum_{r_1\in J(2)}\sum_{i=1}^{I} y_{r_1ln} \cdot z_{i0}^{r_1},\ \forall l \in \{1,\dots,L\},\ n \in \{1,\dots,N-1\} \tag{12}$$

$$\sum_{r_2\in J(1)}\sum_{j=1}^{I} y_{r_2l(n+1)} \cdot z_{ij}^{r_2} \ge \sum_{r_1\in J(2)}\sum_{j=0}^{I} y_{r_1ln} \cdot z_{ji}^{r_1},\ \forall i \in \{1,\dots,I\},\ l \in \{1,\dots,L\},\ n \in \{1,\dots,N-1\} \tag{13}$$

$$t_r(2) = \sum_{i=0}^{I}\sum_{j=0}^{I} (t_r(1) + D_{ij}/v + 2 \cdot t_2) \cdot z_{ij}^{r},\ \forall r \in \{1,\dots,R\} \tag{14}$$

$$\sum_{r=1}^{R} y_{rlN} \cdot \left\lfloor \frac{t_r(2)}{TW} \right\rfloor \le MTW - 1,\ \forall l \in \{1,\dots,L\} \tag{15}$$

$$\sum_{r=1}^{R} x_{rkM} \cdot \left\lfloor \frac{t_r(2)}{TW} \right\rfloor \le MTW - 1,\ \forall k \in \{1,\dots,K\} \tag{16}$$

$$\begin{cases} (t_{r_1}(2)+2\cdot t_1+t_w) \geq t_{r_2}(1) \geq (t_{r_1}(2)+2\cdot t_1), & \sum\limits_{r_1\in J(1)}\sum\limits_{r_2\in J(1)} y_{r_2l(n+1)}\cdot y_{r_1ln}=1 \\ (t_{r_1}(2)+t_1+t_w) \geq t_{r_2}(1) \geq (t_{r_1}(2)+t_1), & \sum\limits_{r_1\in J(2)}\sum\limits_{r_2\in J(1)} y_{r_2l(n+1)}\cdot y_{r_1ln}=1 \\ \left\lfloor \dfrac{t_{r_2}(1)}{TW} \right\rfloor \geq \left\lfloor \dfrac{t_{r_1}(2)+t_1}{TW} \right\rfloor + 1, & \sum\limits_{r_1\in J(1)}\sum\limits_{r_2\in J(2)} y_{r_2l(n+1)}\cdot y_{r_1ln}=1 \\ t_{r_2}(1) \geq t_{r_1}(2), & \sum\limits_{r_1\in J(2)}\sum\limits_{r_2\in J(2)} y_{r_2l(n+1)}\cdot y_{r_1ln}=1 \end{cases}, \tag{17}$$

$$\forall l \in \{1,\ldots,L\},\ n \in \{1,\ldots,N-1\}$$

$$MTW = \left\lceil \frac{T}{TW} \right\rceil \tag{18}$$

$$t_r^1(t) = 1 - \left\lceil \frac{\left| \left(\left\lfloor \frac{t_r(1)}{TW} \right\rfloor \right) - t \right|}{MTW} \right\rceil,\ \forall r \in \{1,\ldots,R\} \tag{19}$$

$$t_r^2(t) = 1 - \left\lceil \frac{\left| \left(\left\lfloor \frac{t_r(2)}{TW} \right\rfloor \right) - t \right|}{MTW} \right\rceil,\ \forall r \in \{1,\ldots,R\} \tag{20}$$

$$t_r^3(t) = 1 - \left\lceil \frac{\left| \left(\left\lfloor \frac{t_r(2)+t_1}{TW} \right\rfloor \right) - t \right|}{MTW} \right\rceil,\ \forall r \in \{1,\ldots,R\} \tag{21}$$

$$KG_i(0) = \begin{cases} CK_i - \sum\limits_{j=1}^{I} Q_{ij}, & CK_i \geq \sum\limits_{j=1}^{I} Q_{ij} \\ 0, & \text{otherwise} \end{cases},\ \forall i \in \{1,\ldots,I\} \tag{22}$$

$$KG_0(0) = PK_0 \tag{23}$$

$$KG_i(t+1) = \begin{cases} 0, & CK_i + \sum\limits_{u=0}^{t}\sum\limits_{r\in J(1)}\sum\limits_{j=1}^{I} z_{ji}^r \cdot t_r^3(u) + \sum\limits_{u=0}^{t}\sum\limits_{r\in J(2)}\sum\limits_{j=0}^{I} z_{ji}^r \cdot t_r^2(u) < \sum\limits_{j=1}^{I} Q_{ij} \\ CK_i + \sum\limits_{u=0}^{t}\sum\limits_{r\in J(1)}\sum\limits_{j=1}^{I} z_{ji}^r \cdot t_r^3(u) + \sum\limits_{u=0}^{t}\sum\limits_{r\in J(2)}\sum\limits_{j=0}^{I} z_{ji}^r \cdot t_r^2(u) - \sum\limits_{j=1}^{I} Q_{ij} - \sum\limits_{u=0}^{t}\sum\limits_{r\in J(2)}\sum\limits_{j=0}^{I} z_{ij}^r \cdot t_r^1(u), & \text{otherwise} \end{cases} \tag{24}$$

$$\forall t \in \{0,\ldots,MTW-1\},\ i \in \{1,\ldots,I\}$$

$$KG_0(t+1) = KG_0(t) - \sum_{r\in J(2)}\sum_{i=1}^{I} z_{0i}^r \cdot z_r^1(t) + \sum_{r\in J(2)}\sum_{i=1}^{I} z_{i0}^r \cdot z_r^2(t), \quad \forall t \in \{0,\ldots,MTW-1\} \tag{25}$$

$$KG_i(MTW) \leq MKG_i,\ \forall t \in \{0,\ldots,MTW\},\ i \in \{1,\ldots,I\} \tag{26}$$

$$CK_i + \sum_{u=0}^{t-1}\sum_{r=1}^{R}\sum_{j=1}^{I} z_{ji}^r \cdot t_r^2(u) - \sum_{u=0}^{t-1}\sum_{r=1}^{R}\sum_{j=0}^{I} z_{ij}^r \cdot t_r^1(u) \le MGC_i, \quad \forall t \in \{0,\dots,MTW\},\ i \in \{1,\dots,I\} \tag{27}$$

$$\sum_{r\in J(2)}\sum_{j=0}^{I} z_{ij}^r \cdot t_r^1(t) \le KG_i(t),\ \forall t \in \{0,\dots,MTW-1\},\ i \in \{0,\dots,I\} \tag{28}$$

$$\alpha_{0j}^k = \sum_{r\in J(2)} x_{rk1}\cdot z_{oj}^r,\ t_r(1) = t_0;\ \forall k \in \{1,\dots,K\},\ j \in \{1,\dots,I\} \tag{29}$$

$$\alpha_{0i}^k \cdot \alpha_{ij}^k = \sum_{r=1}^{R} x_{rk1}\cdot z_{ij}^r,\ t_r(1) = t_0 + D_{ij}/v,\ \forall k \in \{1,\dots,K\}, \quad i \in \{1,\dots,I\},\ j \in \{0,\dots,I\} \tag{30}$$

$$\alpha_{ij}^k \cdot \alpha_{jw}^k = \sum_{r_1=1}^{R}\sum_{r_2=1}^{R} x_{r_1km}\cdot z_{ij}^{r_1}\cdot x_{r_2k(m+1)}\cdot z_{jw}^{r_2},\ t_{r_2}(1) = t_{r_1}(2),\ \forall k \in \{1,\dots,K\}, \quad i \in \{1,\dots,I\},\ j \in \{0,\dots,I\},\ w \in \{0,\dots,I\},\ m \in \{1,\dots,M-1\} \tag{31}$$

$$\alpha_{ij}^k \cdot \alpha_{jw}^k \cdot \alpha_{wu}^k = \sum_{r_1=1}^{R}\sum_{r_2=1}^{R} x_{r_1km}\cdot z_{ij}^{r_1}\cdot x_{r_2k(m+1)}\cdot z_{wu}^{r_2},\ t_{r_2}(1) = t_{r_1}(2) + D_{jw}/v, \quad \forall k \in \{1,\dots,K\},\ m \in \{1,\dots,M-1\},\ i \in \{0,\dots,I\},\ j \in \{0,\dots,I\}, \quad w \in \{0,\dots,I\},\ u \in \{0,\dots,I\} \tag{32}$$

Constraints (2)-(4) are to ensure that each task can only be allocated once to one route. Constraints (5) and (6) are set to guarantee that all the tasks of tractors and trailers are scheduled in sequence, which means that the $m+1$th task of tractor/trailer must be after the mth task. Constraint (7) is to balance the flow in and out of all nodes (including yard and customer depots). Constraint (8) is to make sure that every task has to be fulfilled by one tractor and one trailer. Constraint (9) is to meet all transport demands at customer depots. Constraint (10) is to describe the relationship between the full container tasks and the empty container tasks. Constraints (11)-(13) are constraints for the tasks of trailers: the first one is to ensure that the destination of the previous task must be the starting point for the next task; the second one is to ensure that what is next to the empty container task whose destination is the yard must be the empty container task; the third one is to ensure that what is next to the empty container task whose destination is the customer depot must be the full container task. Constraints (14)-(16) are time constraints for all tasks. Constraint (17) is the time constraints for the tasks of trailers. Constraints (18)-(21) are to define the time window of every task. Constraints (22)-(26) are to determine the number of idled empty trailers at node i and its restrictions. Constraint (27) is to restrict that the number of trailers staying at customer depot anytime should not exceed the maximum number permitted. Constraint (28) is to ensure that in the tth time window, the number of empty container tasks starting from node i should not exceed the idled empty trailers at that time at node i. Constraints (29)-(32) are restrictions on routes and operation times of tractors.

3. **Proposed Heuristic.** This paper proposes a heuristic to solve the complicated problem. In the heuristic, there are two strategies used in the transport system, i.e., ① the Maximum Empty Trailer Demand Prioritized (MEP hereinafter), which means that the customer depot having the maximum demand of empty trailer is chosen as the next task;

② the Minimum Distance Prioritized (MDP hereinafter), which means that the customer depot having the minimum distance with current customer depot is chosen as the next task.

The process of the heuristic is as follows.

***Step* 1**: Initialize all the related parameters, go to *Step* 2.

***Step* 2**: Search for the tractor which completes task first, calculate the time window when the tractor completes its task, and compute the value of $ZG_i(t)$. If $ZG_i(t) > 0$, then go to *Step* 3; otherwise, go to *Step* 4.

***Step* 3**: Compute the value of $GC_i(t)$. If there exists $GC_i(t) < MGC_i$, choose one full loaded trailer by the MEP/MDP strategy, after it completes its full container task, go to *Step* 15; otherwise, go to *Step* 4.

***Step* 4**: Compute the value of KG_i. If $KG_i > MKG_i$, then go to *Step* 5; otherwise, go to *Step* 7.

***Step* 5**: Check if there is any other customer depot which has extra demands for empty trailers. If there exist other customer depots meeting the constraints of $ED_i(t) > 0$ and $GC_i(t) < MGC_i$, choose one customer depot by the MEP/MDP strategy as the destination of the empty container task, complete the empty container task, go to *Step* 14; otherwise, go to *Step* 6.

***Step* 6**: Tractor hangs on an arbitrary trailer at its location to complete the empty container task, and go to *Step* 14.

***Step* 7**: Compute the value of KG_i. If $KG_i > 0$, go to *Step* 5; otherwise, go to *Step* 8.

***Step* 8**: Check if there is any other customer depot which has extra demands for empty trailers. If there exist other customer depots meeting the constraints of $ED_i(t) > 0$ and $GC_i(t) < MGC_i$, choose one customer depot by the MEP/MDP strategy as the destination of the empty container task, complete the empty container task, go to *Step* 14; otherwise, go to *Step* 9.

***Step* 9**: Compute the value of $DGC_i(t)$. If there exists node i with $DGC_i(t) > 0$, go to *Step* 10; otherwise, go to *Step* 11;

***Step* 10**: Choose the nearest customer depot as the tractor's destination, and travel to the depot without carrying anything, go to *Step* 3;

***Step* 11**: Check if there is any other customer depot which has extra demands for empty trailers. If there exist other customer depots meeting the constraints of $ED_i(t) > 0$ and $GC_i(t) < MGC_i$, go to *Step* 12; otherwise, go to *Step* 13.

***Step* 12**: If there is any customer depot or yard with $KG_i(t) > 0$, go to *Step* 10; otherwise, go to *Step* 13.

***Step* 13**: Tractor travels to the yard without carrying anything, go to *Step* 14.

***Step* 14**: If all transport demands of all customer depots are satisfied and the idled empty trailers at all customer depots do not exceed the maximum number, go to *Step* 15; otherwise, go to *Step* 3.

***Step* 15**: Check if all tractors return to the yard. If yes, then terminate the operation; otherwise, tractors which are not at the yard travel to the yard without carrying anything.

4. Numerical Examples.

4.1. Problem scenario.

Based on the operational data of a company, this paper presents the problem scenario as follows. The tractor and trailer transport network consists of a yard and fifteen customer depots. The customer depots are randomly distributed on a $160 * 160$ grid, and the yard is at the centre of the grid $(80, 80)$. The transport demands are also randomly distributed, with the total number of 40. The average travelling speed is 60 km/h, the hanging/unhanging time of trailers is 15 minutes, loading/unloading time

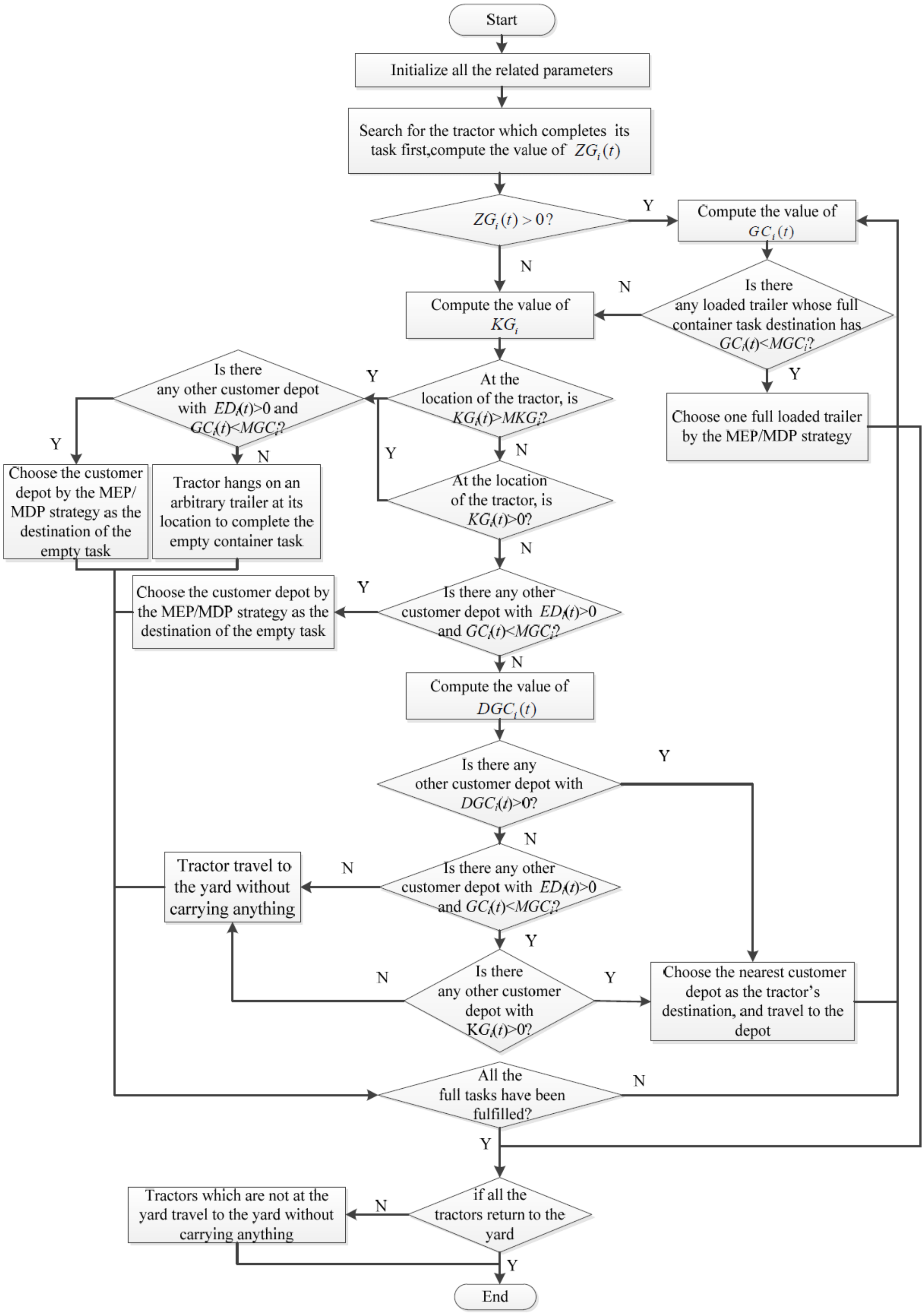
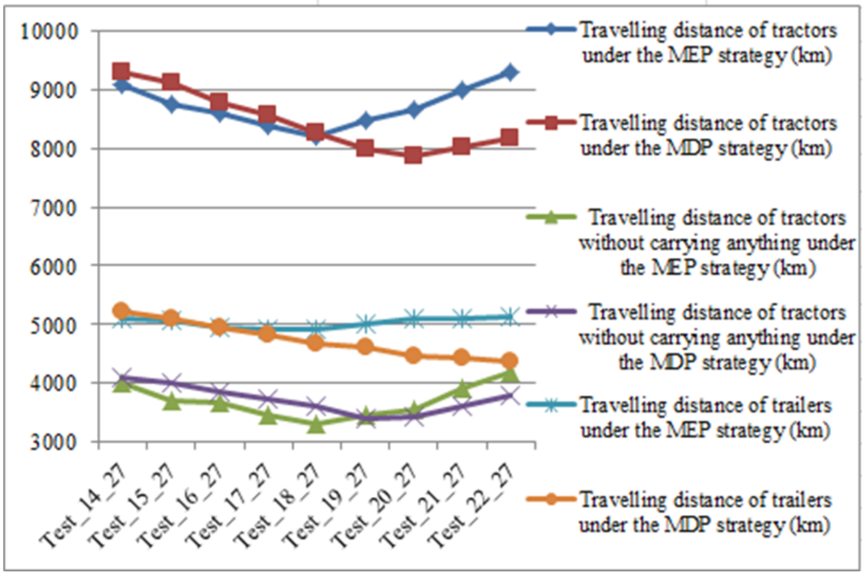


Figure 1. Flowchart of the process of the heuristic

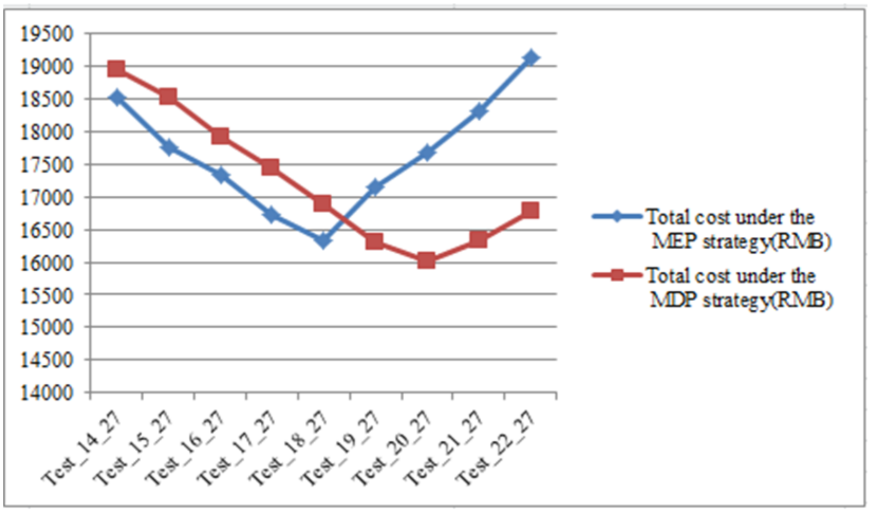
of a unit of cargo is 3 hours, the maximum working hour of a tractor is 24 hours, and the time window is 5 minutes. The transport cost coefficient of tractors travelling without carrying anything is 1.8 RMB/km, and the extra transport cost coefficient of tractors because of pulling trailers is 0.42 RMB/km.

Different scenarios are generated with different numbers of tractors and trailers. In the experiment, tests are named as the format: Test1/2_(the number of tractors)_(the number of trailers) (Therein, 1 means using the MEP strategy; 2 means using the MDP strategy). For example, Test1_14_27 means that in the proposed problem, there are 14 tractors and 27 trailers, and the strategy used in the MEP strategy. The heuristic is designed at Matlab 2010, and the running environment is PC (Intel® Core® processor i5, 2.1 GHz).

4.2. **Results analysis between the two strategies.** Figure 2 shows comparison of results for tractors and trailers with different numbers of tractors between the MDP strategy and the MEP strategy.



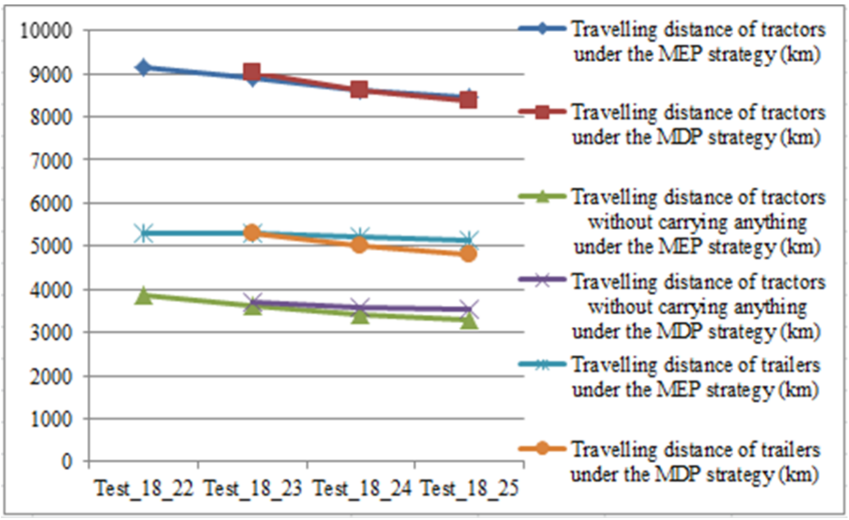
(a) Travelling distances



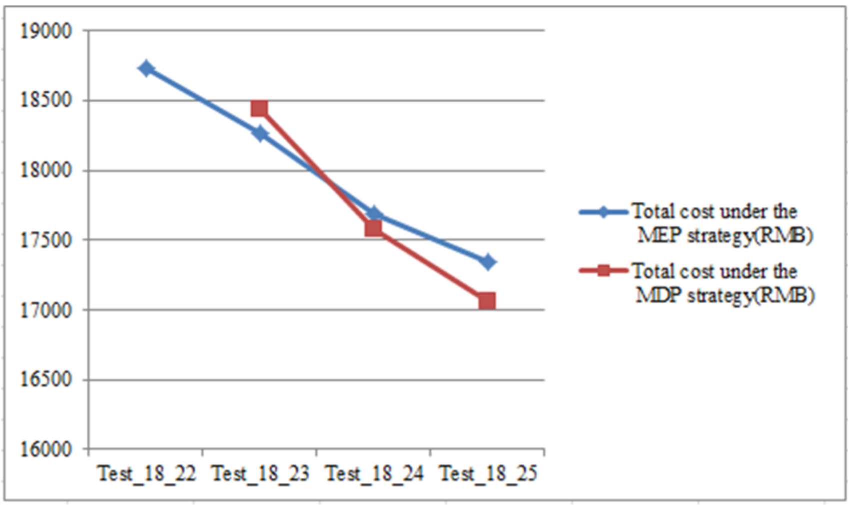
(b) Total costs

FIGURE 2. Travelling distances and total costs with different numbers of tractors

Taking the result under the MEP strategy as an example, it can be seen that the number of tractors has a direct influence on tractors and trailers' travelling distance, and thus on total cost. When the number of tractors is 18, and the number of trailers is 27, the total cost is the minimized among different tests. When the number of tractors increases from 14 to 18, the overall trend of travelling distance of tractors, travelling distance of tractors without carrying anything, travelling distance of trailers, and the total cost is decreasing. That is because if the number of tractors is not enough, tractors start with only parts of empty trailers, leading many empty trailers at the yard. When there is demand for empty trailer, it is necessary for trailer to return to yard to fetch an empty trailer. Because of this, the travelling distance of tractors without carrying anything increases, and thus increases the total cost, etc. However, when the number of tractors increases from 19 to 22, the overall trend of the four indicators tends to increase; and the faster the number of tractors increases, the faster the travelling distance of tractors increases. This demonstrates that under the circumstances of limited operation tasks, excessive tractors will lead to extra travelling without carrying anything to the yard, and thus cause the increase of the total cost.



(a) Travelling distances



(b) Total costs

Figure 3. Travelling distances and total costs with different number of trailers

Figure 3 shows comparison of results for tractors and trailers with different numbers of trailers between the MDP strategy and the MEP strategy. It can be seen that when the number of tractors is 18, and the number of trailers is 25, the total cost is the minimized among different tests. When the number of trailers decreases from 25 to 22, the total cost increases accordingly; and when the number of trailers decreases to 22, the solution is the infeasible solution. That means that if the number of trailers is not enough, tractors finishing their tasks have to return to the yard to wait for trailers completing the loading/unloading operation. That leads to extra travelling of tractors and inevitable increase of total costs.

Besides, when the number of tractors is 18, and the number of trailers is 23-25, the travelling distance of trailers under the MEP strategy is larger than that under the MDP strategy, while the travelling distance of tractors without carrying anything under the MEP strategy is lower than that under the MDP strategy. It can be seen that when the number of trailers is 22 and 23, the total cost under the MEP strategy is lower than that under the MDP strategy; when the number of trailers is 24 and 25, the total cost under the MEP strategy is larger than that under the MDP strategy.

Thus, it is recommended that when the number of tractors is predetermined, and the number of trailers is not enough, it is advised to use the MEP strategy to get a scheduling plan for the transport; when the number of trailers is enough, it is advised to use the MDP strategy to get the scheduling plan.

5. **Conclusions.** The tractor and trailer transport has the unique characteristic of "synchronized operation by multi-machines". This paper proposed a combined scheduling model in the tractor and trailer transport under the cycle mode considering the unique characteristic. A heuristic algorithm was proposed to solve the problem. Numerical experiments were carried out to testify the effectiveness of the proposed mathematical model and algorithm. Sensitivity analysis on key parameters shows the effect of different scheduling rule and proportion of tractor-to-trailers on transport cost. Results of the numerical examples show that when the number of tractors is predetermined, and the number of trailers is not enough, it is advised to use the MEP strategy to get a scheduling plan for the transport; when the number of trailers is enough, it is advised to use the MDP strategy to get the scheduling plan. The conclusions may be useful for practical decisions on what kind of strategy should be applied to getting a best scheduling plan.

Future work may focus on considering realistic constraints such as the influence of real-time traffic information on decision-making.

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