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Sustainable maritime crude oil transportation: a split pickup and split delivery problem with time windows

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Abstract

This paper studies a novel sustainable vessel routing problem modeling considering the multi-compartment, split pickup and split delivery, and time windows concepts. In the presented problem, oil tankers transport crude oil from supply ports to demand ports around the globe. The objective is to find ship routes, as well as port arrival and departure times, in a way that minimizes transportation costs. As a second objective, we considered the sustainability aspect by minimizing the vessel energy efficiency operational indicator. Multiple products are transported by a heterogeneous fleet of tankers. Small realistic test instances are solved with the exact method.

Keywords: Sustainable transportation, Maritime crude oil, pickup and delivery, multi-objective problem, EEOI

1. Introduction

According to the International Energy Agency [28], over the past century, the growth in the global economy has an impact on the environment, that led to increased use of energy and emissions of greenhouse gases (GHG).
The International Transport Forum [29] estimated that maritime transport is responsible of 873 million tonnes of CO2 per year [29], according to [27] ships accounted for approximately 1 billion tonnes of GHG emissions over the period 2007 to 2012. Besides, oil tankers make approximately 114 million tonnes of CO2 [26], about 13% of maritime emissions.
In this paper, a Multi-Compartment Vehicle Routing Problem (MCVRP) in maritime transportation is addressed. In ship routing problems, the multiple compartments concept is commonly used due to its importance in the transportation of different products via large ships. In fact, ships pick up the products to be transported from supply ports, then deliver them to demand ports based on a schedule. Besides, ships are loaded with different types of products, in sepa-

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rate compartments with fixed sizes [25], then these compartments are shared between customers.
In recent literature, most to ship routing problems studies considered multi-compartments with flexible products assignment. In the crude oil transportation domain, refineries order crude oil to produce a panoply of petroleum products [10]. For this reason, they require different quality of crude oil, thus, the transportation planning needs to be treated as multi-compartment. Furthermore, several papers have studied the problem of minimizing the CO2 and GHG emission as key sustainability aspect to avoid the most catastrophic impacts of climate change.
In [15], the authors proposed a mixed integer non-linear programming model that includes the issues pertaining to multiple time horizons, sustainability aspects and varying demand and supply at various ports. They proposed an effective particle swarm optimization-composite particle metaheuristic to solve the problem. In their paper, they integrated the carbon emission, fuel cost and fuel consumption constraints to the mathematical model for encapsulating the sustainability dimensions.
The sustainability in maritime transportation problem was presented in [17], the authors studied a multi-objective ship routing and scheduling problem that includes time window concept. To tackle the problem, they developed a sorting genetic algorithm II (NSGA-II) and particle swarm optimization metaheuristics. [19] addressed the sustainable ship routing problem considering a time window concept and bunker fuel management. The objective is reducing carbon emissions within the maritime transportation domain. The problem is solved with a hybrid particle swarm optimization and a basic variable neighborhood search algorithm.
The maritime transportation sector is a significant emitter of carbon dioxide, the amount of which is directly proportional to fuel consumption. The International Maritime Organization (IMO) introduced the Energy Efficiency Operation Index (EEOI) in 2009 [4] and encouraged the voluntary use of this metric in order to facilitate the evaluation of CO2 emission and fuel efficiency. Consequently, EEOI is further highlighted in 2016 [30]. The EEOI is originally formulated for policy purposes by the European Commission's proposal between EU ports [14]. The basic formulation of the EEOI for a ship journey is defined as the mass of CO2 per unit of transport work, i.e. grams of CO2 emission per barrel-nautical miles [18].

2. Problem description

Global shipping companies plan vessels' routes and schedules in a particular planning horizon to reduce the overall transportation cost, see figure 1. On the other hand they take into account the sustainability aspects. In this context, our model considers two objectives which are the minimization of the voyage costs $Total_{cost}$ that covers the travel costs (in the sea) C^{Sea} and port costs C^{Port} and the minimization of the EEOI.

$$min \quad Total_{cost} = C^{Sea} + C^{Port} \tag{1}$$

Travel costs C^{Sea}

- Sailing cost C_1. Incurs the sailing cost for vessel v on an entire route.
- Sea fuel cost (traveling) C_2. Depicts the fuel consumption cost for vessel while sailing in sea
- Sea fuel cost (waiting) C_3. Accounts the fuel consumption for the waiting time (idle).

where:

- C^v: route cost for vessel v
- F_v^{sea} fuel consumption rate while sailing per unit time for vessel v
- T_{ij}: travel time between ports i and port j
- F_v^{wait}: fuel consumption rate while waiting per unit time for vessel v
- wt_{iv}: vessel v waiting time at port i

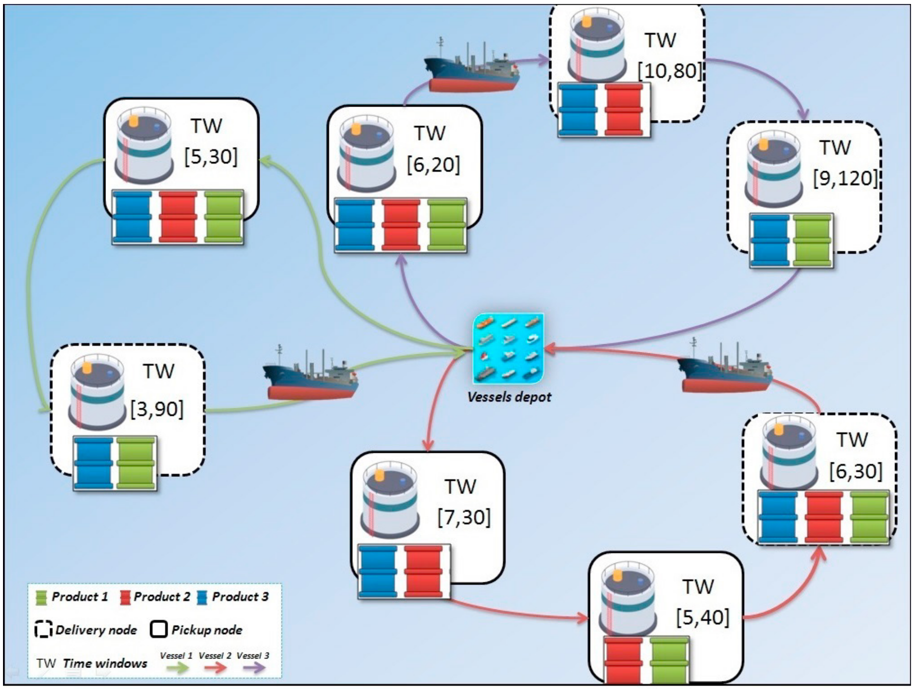

Fig. 1. Maritime crude oil transportation

$$C^{Sea} = \overbrace{\sum_{v\in V}\sum_{i\in N}\sum_{j\in N} C^v x_{ijv}}^{C1} + \overbrace{\sum_{v\in V}\sum_{i\in N}\sum_{j\in N} F_v^{sea} t_{ij} x_{ijv}}^{C2} + \overbrace{\sum_{v\in V}\sum_{i\in N} F_v^{wait} wt_{iv}}^{C3} \tag{2}$$

Port costs C^{Port}

- Handling cost C_4. Covers the variable part of the costs in a port. The fuel consumption in a port depends on the amount of handled cargo.
- Port operating cost C_5. Depicts the fixed cost for performing port's loading/unloading operation.
- Docking cost C_6. Provides a port's docking charges.

where:

- C_i^q: cost per weight unit for pickup or delivery in port i
- q_{ip}: requirement: cargo weight to be picked up/delivered of product p in port i
- y_{iv}: Binary variable; = 1, if vessel v visit port i and 0 otherwise
- R_{iv}: fixed cost for performing loading/unloading operation of vessel v at port i
- O_{iv}: docking cost of a vessel v
- st_i: vessel service time at port i

$$C^{Port} = \overbrace{\sum_{v\in V}\sum_{i\in N} C_i^q q_{ip} y_{iv}}^{C4} + \overbrace{\sum_{i\in N}\sum_{v\in V} R_{iv} y_{iv}}^{C5} + \overbrace{\sum_{i\in N}\sum_{v\in V} O_{iv} y_{iv} st_i}^{C6} \tag{3}$$

The Energy Efficiency Operation Indicator (EEOI), one of schemes as a monitoring performance indicator related to the vessel energy efficiency management plan which is the mandatory regulation for vessels in operation, intending to reduce greenhouse gas emissions in maritime transportation. It is closely related to vessel speed and the waterway environment, among other factors. Finding the optimal main engine speed is a basic way to improve energy efficiency and reduce the EEOI [21]. The EEOI, an important indicator of vessel energy efficiency stipulated by the international maritime organization, was firstly introduced in 2011 [4] as follows, where:

- F_{ijv}: the fuel consumption for vessel v on arc (i, j)
- C_F: conversion factor between fuel consumption and $CO2$ emission
- $Dist_{ij}$: distance between port i and j
- S_s: average sailing speed

$$min \quad \frac{\sum_{v\in V}\sum_{i\in N}\sum_{j\in N} F_{ijv}.C_F}{\sum_{v\in V}\sum_{i\in N}\sum_{j\in N} S_s Dist_{ij}} x_{ijv} \tag{4}$$

Fuel consumption. According to [18], fuel consumption F_{ijv}, can be expressed as follows, where:

- S_v: design speed for vessel v
- ∇_{ijv}: vessel v's displacement on arc (i, j)
- ∇_v: the full load displacement for vessel v
- F_{dv}: the design daily fuel consumption at design speed for vessel v
- T_{ij}: travel time between ports i and port j

$$F_{ijv} = (\frac{S_s}{S_v})^n.(\frac{\nabla_{ijv}}{\nabla_{di}})^{2/3}.F_{dv}.T_{ij} \tag{5}$$

Concerning the constraints, we consider the multi-compartment constraints, split pickup and split delivery constraints, time windows constraints, and the vessel routing constraints as given in [10].
Multi-compartment, pickup and delivery constraints. impose both the capacity and connectivity of the feasible arcs [20] [9].
Cargo restrictions and vessel load balance constraints. restrict cargo weight and volume on arcs. The total cargo amount onboard a vessel has to be less than or equal to a weight or volume limit. Each arc has a cargo weight, cargo volume or both, cargo weight and volume, restriction.
Vessel routing constraints. ensure that each port is visited by exactly one vessel, and the continuity of each route, that is: a vessel that visits a port must leave it, it guarantees the continuity of vessel' pathways. Then, it states that if there is a vessel travel from port 1 to port 2, they are visited by the same vessel.
Time windows constraints. represent a soft time windows constraints. It guarantees that the serves to a port must be within a given time windows. Also, it ensures that the starting time of the next port has to consider the start serve time plus the waiting time and the service time of the previous port, in addition to the travel time between the two ports.

3. Experimental study

We present in this section the results of randomly generated instances using Ilog CPLEX. The instances parameters' values were tuned based on the ranges reported in table 3. In table 1, we report more details about the artificial instances;

- the number of ports are between 5 and 20
- vessels are between 3 and 9

- two categories of product numbers $|P|$: 2 and 3
- Two ranges of the Pickup & delivery: $[30\%, 70\%]$ and $[50\%, 50\%]$
- three types of time windows: Without Time windows (WTW), Narrow Time windows (NTW), and Time windows (TW)

Our experiments were executed on a personal computer with $Intel\ Core^{TM}$ i7-4610M CPU @ 3.00GHz 3.00GHz 16 GB RAM and Windows 8.1 pro, 64-bit operating system, x64-based processor.
We considered a vessel named MARPOL tanker of IMO's oil tanker classification, shown in figure 2. The ship characteristics are given in table 2.
Table 4 reports the generated solution values. $Inst.$ refers to the instance name, n, v are respectively the number of ports and vessels, p is the number of the considered products, P/D are the number of pickup and delivery ports respectively, and TW is the time windows type for that instance.
In this table we recorded the total cost, $opt.$, means that the obtained result is an optimal solution, the different costs, and the EEOI value for that solution.
We plotted in figure 3 the graphical representation of the results showing the impact of the time windows types on the total cost. We can notice from this figure that the narrow time windows (NTW) requires the highest cost comparing to the other two types of time windows.
In figure 4, we pointed out the impact of the time windows types on EEOI. We can see that in the NTW instances the EEOI is higher than the WTW instances and TW instances. Hence, we can conclude that if the time windows is more tight, the it has a negative impact on the environment, as the vessel needs to use the maximum allowed speed.
There are many different methods for multi-objective optimization, as a common concept, minimizing a weighted sum constitutes an independent method as well as a component of other methods. In this study we used the weights as the equation bellow.

$$Min\ \ w_1 * obj_1 + w_2 * obj_2 \quad where \quad w_1 + w_2 = 1 \tag{6}$$

The bi-objective model was assessed using multi-objective metrics. These metrics are detailed in what follows. Table 5 reports the multi-objective performance metrics.

- Cardinality of the Pareto set (Card): This metric is to measure the cardinality of the potentially efficient set, it counts the total number of non-dominated solutions.
- Diversification metric (Div): The diversification metric (Div) is to indicate the diversity of the Pareto solutions. The Div is calculated using the following equation.

$$Div = \sqrt{\sum_{i=1}^{N_{obj}} (\max_{j=1..card}\{obj_i^j\} \min_{j=1..card}\{obj_i^j\})^2} \tag{7}$$

- Spacing (Sp): The spacing metric is to determine the distribution of solutions in an obtained Pareto Front.

$$Sp = \sqrt{\frac{1}{Card-1} \sum_{i=1}^{Card} (\bar{d} - d_i)^2} \tag{8}$$

Ports, Vessels	$\lvert P \rvert$	Pickup & delivery	Time windows
5 , 3	2	30% , 70%	Without Time windows (WTW)
10 , 4	3		Narrow Time windows (NTW)
15 , 7		50% , 50%	Time windows (TW)
20 , 9			

Table 1. Artificial instances

Fig. 2. The oil tanker: MARPOL tanker of IMO's oil tanker classification

MODEL DIMENSIONS	
Length overall	183cm
Breadth	30cm
Depth	15.8cm
Draught	10.6cm
Freeboard	5.2cm

Table 2. Ship characteristics

$$d_i = \min_k \sum_{m=1}^{N_{obj}} |obj_m^i - obj_m^k|, k = 1, .., Cardandi \neq k \tag{9}$$

- Time (Avg time): The average computing time reported by the tested methods

4. Conclusions

In this paper we studied a new multi-objective version of the sustainable vessel routing problem. The first objective encompasses different costs related to vessel sailing and docking time at port. The second objective is the minimization of the greenhouse emissions expressed with the vessel energy efficiency operational indicator. The considered constraints are related to multi-compartment, split pickup and split delivery, and time windows concepts. The pro-

Parameter or variable		Range	Unit
Cost per weight unit for operations	C_i^q	[2,8]	USD/Gallon
Requirement: cargo weight	q_{ip}	[500,1000]	Gallon
Route cost for sailing	C_{ij}^v	[30,80]	USD
The docking cost	O_{iv}	[100,500]	USD/hours
Maximum allowed cargo weight	W_{ijv}	[2000,4000]	Gallons
Maximum allowed cargo volume	V_{ijv}	[16.7,33.38]	Kg/Gallon
Density of product	D_p	119.826	Kg/Gallon
Travel time between ports	t_{ij}	[12.18]	hours
Distance between ports	Dis_{ij}	[300.500]	Nautical Miles (nm)
Fuel consumption rate while sailing	F_v^{sea}	[30,80]	USD/nm
Fuel consumption rate while waiting	F_v^{wait}	[10,50]	USD/hours
Design speed for vessel	S_v	30	knots
Vessel type specific power parameter	g	3	-
Design daily fuel consumption	F_v		
Sufficiently large number	M	1000	-
Average sailing speed	S_{ijv}	{12,16,22}	knots

Table 3. Artificial instances ranges

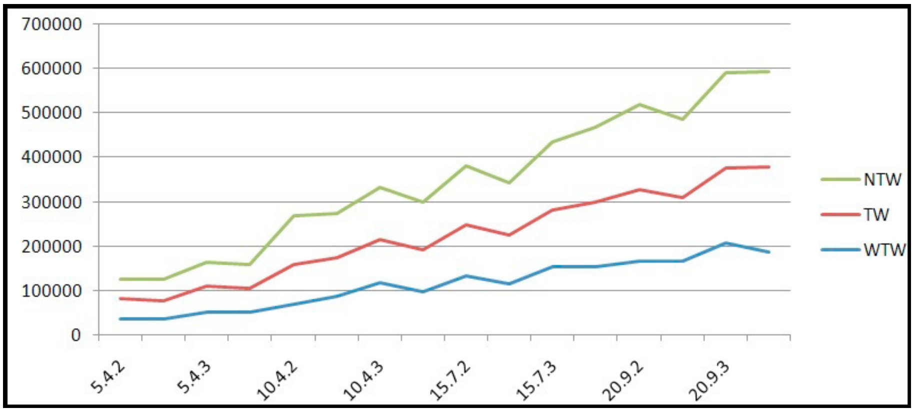

Fig. 3. Graphical representation of the results: the impact of the time windows on the total cost

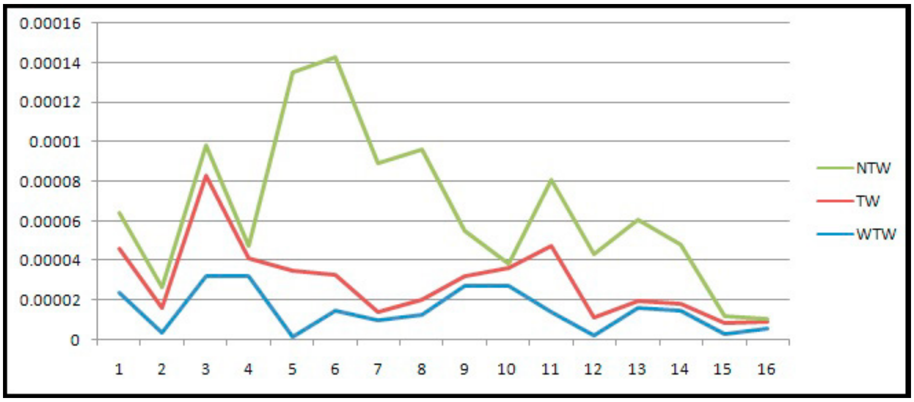

Fig. 4. Graphical representation of the results: the impact of the time windows on the EEOI

Inst	n,v	p	P/D	$T.W.$	CPLEX		Costs (USD)							EEOI
					$Total_{Cost}$	$Type$	Sea costs				Port costs			
							C_1	C_2	C_3	#	C_4	C_5	#	
C_{01}	5,4	2	2/3	WTW	35618	Opt.	303	12408	1548	14259	20058	1302	21360	24.6×10^{-5}
C_{02}				NTW	43124	Opt.	296	15530	126	15952	26095	1077	27172	18.57×10^{-5}
C_{03}				TW	46156	Opt.	301	15733	190	29233	28927	1006	16224	22.52×10^{-5}
C_{04}			3/2	WTW	35840	Opt.	339	20060	390	20789	13710	1341	15051	39.2×10^{-6}
C_{05}				NTW	48434	Opt.	325	19975	2409	22709	24329	1396	25725	11.88×10^{-5}
C_{06}				TW	39.898	Opt.	302	13590	0	13892	24840	1167	26007	12.31×10^{-5}
C_{07}		3	2/3	WTW	52046	Opt.	322	14235	2175	16732	33867	1447	35314	32×10^{-5}
C_{08}				NTW	55428	Opt.	320	20874	378	21572	32690	1167	33857	15.9×10^{-5}
C_{09}				TW	56259	Opt.	298	14450	929	15677	38998	1585	40583	51.44×10^{-5}
C_{10}			3/2	WTW	50531	Opt.	285	18450	580	19315	29712	1504	31216	32.8×10^{-5}
C_{11}				NTW	55663	Opt.	350	21394	0	21744	32467	1452	33919	61.05×10^{-6}
C_{12}				TW	52578	Opt.	300	24043	770	25113	26436	1029	27465	93.4×10^{-6}
C_{13}	10,4	2	3/7	WTW	68697	Opt.	571	19770	–	20341	45801	2555	48356	17.8×10^{-6}
C_{14}				NTW	111596	Opt.	977	62263	0	63240	45801	2555	48356	0.001
C_{15}				TW	87878	Opt.	776	37442	1304	39522	45001	2555	48356	33.226×10^{-6}
C_{16}			5/5	WTW	86804	Opt.	830	38267	2672	41769	42510	2525	45035	15×10^{-5}
C_{17}				NTW	99180	Opt.	917	48016	39	48972	47587	2621	50208	0.0011
C_{18}				TW	87092	Opt.	765	36119	0	36884	47587	2621	50208	17.77×10^{-6}
C_{19}		3	3/7	WTW	118122	Opt.	805	45636	1484	47925	66713	3484	70197	10.7×10^{-5}
C_{20}				NTW	117640	Opt.	853	56594	102	57549	57106	2985	60091	75.1×10^{-5}
C_{21}				TW	96082	Opt.	638	29240	2734	32612	60980	2490	63470	41.17×10^{-6}
C_{22}			5/5	WTW	97641	Opt.	813	30299	1799	32911	62317	2413	64730	13.8×10^{-5}
C_{23}				NTW	107008	Opt.	963	41192	124	42279	62317	2413	64730	76.06×10^{-5}
C_{24}				TW	92820	Opt.	746	26994	250	28090	62317	2413	64730	71.78×10^{-6}
C_{25}	15,7	2	5/10	WTW	131874	Opt.	1308	79464	1330	82102	45398	4374	49772	27.9×10^{-5}
C_{26}				NTW	133428	Opt.	1346	80757	1553	83656	45398	4374	49772	23.711×10^{-5}
C_{27}				TW	115764	Opt.	1148	58914	65	60127	51562	4075	55637	49.15×10^{-6}
C_{28}			7/8	WTW	–	Opt.	–	–	–	–	–	–	–	–
C_{29}				NTW	117064	Opt.	1053	60633	189	61875	51356	3833	55189	23.6×10^{-6}
C_{30}				TW	111609	Opt.	1007	54447	1080	56534	51046	4030	55076	93.78×10^{-6}
C_{31}		3	5/10	WTW	151938	Opt.	1381	70320	1170	72871	74993	4075	79068	14.5×10^{-5}
C_{32}				NTW	155612	Opt.	1443	74872	229	76544	74993	4075	79068	34.3×10^{-5}
C_{33}				TW	128217	Opt.	1007	57862	625	59494	64408	4315	68723	33.8×10^{-6}
C_{34}			7/8	WTW	152242	Opt.	1325	80356	1260	82941	65125	4176	69301	25.87×10^{-6}
C_{35}				NTW	167507	Opt.	1417	85507	229	87153	76401	3954	80355	33.07×10^{-5}
C_{36}				TW	146995	Opt.	1070	64248	65	65383	77231	4381	81612	82.72×10^{-6}
C_{37}	20,9	2	6/14	WTW	165320	Opt.	1766	83956	3764	89486	70305	5529	75834	16.24×10^{-5}
C_{38}				NTW	192174	Opt.	2023	116060	354	118440	67996	5737	73733	41.03×10^{-5}
C_{39}				TW	162259	Opt.	1557	82740	369	84666	71647	5946	77593	34.16×10^{-6}
C_{40}			10/10	WTW	164200	Opt.	1781	83256	4926	89963	68683	5555	74238	15.6×10^{-5}
C_{41}				NTW	177552	Opt.	1988	103750	159	10590	66039	5618	71657	30.7×10^{-5}
C_{42}				TW	143922	Opt.	1619	71710	.875	74204	64335	.5384	69719	29.96×10^{-6}
C_{43}		3	6/14	WTW	–	Opt.	–	–	–	–	–	–	–	–
C_{44}				NTW	215900	Opt.	1997	111020	354	113370	97257	5270	102530	42.72×10^{-6}
C_{45}				TW	169581	Opt.	1579	76779	785	79143	85119	5319	90438	51.76×10^{-6}
C_{46}			10/10	WTW	185956	Opt.	1666	81311	5110	88087	92450	5419	97869	56.7×10^{-6}
C_{47}				NTW	215366	Opt.	1977	101120	354	103450	10670	5216	111920	23.5×10^{-6}
C_{48}				TW	192338	Opt.	1609	86030	449	88088	98869	5381	104250	31.5

Table 4. Computational results

Ports	Vessels	$\|P\|$	$Card$	Div	SP	Time (s)
5	3	2	3	5	1.68069	1.82
5	3	3	4	6	1.71069	1.92
10	4	2	5	8	1.8895	4.9
10	4	3	5	10	1.98910	4.11
15	7	2	6	11	1.08069	5.81
15	7	3	8	13	1.5238	6.56
20	9	2	9	12	1.6069	9.73
20	9	3	11	12	1.8654	11.43

Table 5. Multi-objective performance metrics

posed model is tested on CPLEX using random generated instances based on a real case study. The computational results show that the narrow time windows requires the highest cost and greenhouse emissions.

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