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Development of a Vessel Scheduling Optimization Model to improve Maritime Transport sustainability

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A B S T R A C T

The social and economic development of the islands is generally dependent on the interconnection level with the mainland obtained through maritime transport services. When connecting many islands, the route planning is essential and typically a variety of constraints must be considered. Various optimization methods have been established to improve cost-efficiency but today environmental concerns, like the reduction of CO_2 emissions, have become mandatory. This paper proposes a vessel scheduling optimization model able to simultaneously consider compulsory and optional tasks and vehicle-dependent profits. The algorithm was applied to seven islands of the Tyrrhenian Sea located in front of Sicily, named “Aeolian Islands”. Considering the regional requirements in terms of minimum number of routes and maximum fare prices for each season, this research compared the optimal vessels option obtained maximizing the profit with the one obtained minimizing the emissions. In particular, we have conducted three different analyses, in the first one we have considered only the mandatory routes while the second one was carried out identifying a series of potentially attractive additional activities based on historical demand data provided by the company that currently manages the service. Finally, the third analysis addresses a scenario where older fuel-powered vessels were replaced with hybrid electric ones.

1. Introduction

The 2030 Agenda for Sustainable Development, with its 17 Sustainable Development Goals (SDGs), offers an impressive program that opens new and widespread opportunities for reducing greenhouse emissions in different sectors. The transport sector is one of the most polluting sectors worldwide, accounting for about 25% of greenhouse gas (GHG) emissions from energy in 2019 [1]. Maritime transport is an important subsector and tourism is the largest maritime activity in Europe representing over one third of the maritime economy [2]. This sector is characterized by many Small and Medium Enterprise (SME) which are faced with numerous challenges [3]. Among these, the main ones are the dependence on specific regional requirements, the low added value generated, the need for renewed marketing approaches and the upgrading of obsolete fleet and infrastructures, for which however investment capacity is very limited [4]. In addition, seasonality of services, as well as inter-island connectivity, pose further challenges [5]. Many of these issues are daily faced by maritime operators connecting the numerous islands in the sea around Sicily. An optimized connection plan between the islands and the mainland could produce benefits both for shipping companies as well as the growth of the islands' economy and tourism [6].

The Vehicle Scheduling Problem (VSP) is a decision problem arising at the tactical level, consisting of assigning a set of timetabled trips to a set of vehicles. Trips are characterized by a departure location, a set of stops and an arrival location. Generally, starting and arrival time of trips is fixed and given as an input. However, in some applications, those times are not strictly fixed but a narrow time window for the starting time of the trip (and consequently on the arrival time) is provided. The objective is to minimize the total costs, ensuring that each trip is executed, within its predefined time window, and that each vehicle performs a feasible sequence of trips. Total costs can be defined as a combination of fixed cost for vehicle usage, variable costs for mileage covered, which can be differ among vehicles or category of vehicles, and eventually, penalty costs for soft constraints violation. For a survey on VSPs, we refer the reader to Bunte and Kliewer [7]. Specific applications of vehicle scheduling to maritime transportation (also known under the name of vessel scheduling) have been reviewed in Dulebenets et al. [8].

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The main difference with classical VSP is that the vehicle speed is treated as a decision variable itself. This is realistic in case of private companies performing their network design but does not apply in our case in which the company has to fulfill a specific request coming from the regional government in which travel times, and consequently speed, are imposed. In fact, sailing at a lower speed respect to those requested would increase travel times and create a disservice for passengers, while adopting a higher speed would increase customers' discomfort due to the higher vibrations perceived during the sailing. Vessels speed optimization has been considered as a decision variable also in Wang and Xu [9], where voyage chartering is addressed, adn in Mancini and Stecca [10] where the authors addressed the problem of designing and attractive portfolio of cruise itineraries for a cruising company. In Fadda et al. [11] the design of a maritime hub and spoke network in the Mediterranean Sea, and the associated services scheduling plan, are addressed. However, the scheduling component of the problem is not related to the assignment of tasks to single vehicles, but only concerns the timetable planning, therefore the problem addressed is different from ours.

The basic version of the VSP, presented by Saha [12] considers trips starting and ending at the same depot and a set of identical vehicles (VSP-SD). This problem introduces very strong assumptions and therefore its applicability to real cases is rather limited. In Gintner et al. [13], the authors introduce a model able to minimize the number of vehicles used. In case the maximum number of available vehicles is not sufficient to cover all of the trips, the model maximizes the number of covered trips, and provide a feasible schedule for vehicles along with a list of the unserved trips. Bertossi et al. [14] introduced an extension of VSP in which multiple depots are considered, which can act as starting and/or arrival point of trips. Another common extension, which arises in practical applications, concerns the presence of multiple vehicle types (MVT), characterized by a potentially different fixed and/or operational cost. A maximum number of available vehicles for each type is considered. A further extension, introduced by Forbes et al., [15] and named VSP with vehicle type groups (VSP-VTG), considers compatibility between trips and vehicle types, i.e. it includes the cases in which a trip can be execute only by a subset of the vehicle types, which meet some specific requirements, such as, for instance the minimum passengers capacity. Hassold and Ceder [16] studied a further version of VSP-VTG in which trips' starting (and arrival) times are not fixed but must be determined by the model within a feasible time window. In all the above-mentioned problems, all the trips must be performed. However, there are many applications in which this is not a mandatory constraint, but a profit is associated to each performed trip and the goal is to select the trips to perform and provide a feasible schedule in order to maximize the total profit which is given by the sum of profit minus the operational costs. Despite the great applicability of this problem setting in the real world, it has not yet been extensively researched in the literature. The first to address this feature have been Mancini and Gansterer [17], who introduced it in the context of vehicle scheduling for rental-with-drivers services. The case in which only a subset of the tasks is compulsory while the others are optional but generate profit if fulfilled, has not been addressed so far in the context of vehicle scheduling. Moreover, in Mancini and Gansterer [17] the profit achievable performing a task does not depend on the vehicle used to fulfill it, whereas we consider a vehicle-dependent profit associated to tasks. This is given by the fact that the profit obtainable depends on the number of passengers can use the service, which is limited by the capacity of the vessel, which vary among vessels.

This research introduces the vehicle scheduling problem with optional tasks and vehicle dependent profits. The novelty of the model with respect to the current literature, is twofold. Firstly, we consider both mandatory and optional services. Secondly, we consider a vehicle-dependent profit. The developed model was implemented on the area consisting of seven islands all situated on the Tyrrhenian Sea in front of Sicily. These are the Aeolian Islands that comprising (in size order) Lipari, Salina, Vulcano, Stromboli, Filicudi, Alicudi and Panarea. They are connected to Sicily via the port of Milazzo and to Calabria via the port of Vibo Valentia. The shipping company Liberty Lines operates a high-speed passenger service following the minimum requirements set by the Sicilian region. Considering the limited research in the field and in the area of study, this research will thus serve as a preliminary attempt to optimize Aeolian islands connection service and the model developed can be implemented for all the other Mediterranean Islands.

2. Problem Description and Mathematical Formulation

2.1. Problem Description

The problem we address consists of assigning a set of tasks (i.e the routes) I, composed by subset of compulsory tasks I^c and a set of optional ones I^o, to a set of heterogeneous vessels K. All tasks in I^c must be performed, while tasks in I^o are optional but generate a profit if executed. Such profit, p_{ik}, may vary depending on the vehicle k with which it is performed. Each task is associated with a departure and a departure and an arrival port, namely si and ai, a departure time window $[ei, li]$, a travel distance di, and a travel time ti. The cost of performing task i with vehicle k depends on the consumption rate of k and is identified as cik. Analogously, the emissions generated performing task i with vehicle k, is defined as uik, which depends on the unitary emission for mile associated to k.

The fuel consumption rate of the vehicle k determines the cost cik of performing task i with vehicle k; while the unitary emission for mile associated to k affects the emissions uik generated by vehicle k while performing task i.

We suppose that all the vehicles are located at a single depot. For operational reasons, we define a dummy task,0, with starts and end at the depot, and have null cost, travel time and emissions. We define I0 as the set containing all the tasks plus the dummy task, i.e. $I \cup \{0\}$ For each pair of tasks, i and j, in I0, are known costs and emissions necessary to reach sj from ai with each vehicle k, defined, respectively, as $\widetilde{c_{ijk}}$, $\widetilde{u_{ijk}}$, as well as the travel time from i to j, $\widetilde{t_{ij}}$. Furthermore, to consider specific requirements associated to tasks, a compatibility indicator φ_{ik} ,which is equal to 1 if task i can be executed by vehicle k, is given in input. The goal is to maximize the total profit, defined as the collected revenues minus the costs.

2.2. Mathematical Formulation

The decision variables involved in the mathematical formulation are reported in the following:

- *Xijk*: binary variable taking value 1 if task j is executed immediately after task i by vehicle k, and 0 otherwise.
- *Yik*: binary variable taking value 1 if task i is assigned to vehicle k, and 0 otherwise.
- *Ti*: non negative continuous variable representing starting time for task i.

To improve the readability of the model we define two auxiliary decision variables, "profit" and "emissions", as follows:

$$\text{profit} = \sum_{i \text{ in } I} \sum_{k \text{ in } K} (p_{ik} Y_{ik} - c_{ik} Y_{ik}) - \sum_{i \text{ in } I0} \sum_{j \text{ in } I0} \sum_{k \text{ in } K} \widetilde{c_{ijk}} X_{ijk}$$

$$\text{emissions} = \sum_{i \text{ in } I} \sum_{k \text{ in } K} u_{ik} Y_{ik} + \sum_{i \text{ in } I0} \sum_{j \text{ in } I0} \sum_{k \text{ in } K} \widetilde{u_{ijk}} X_{ijk}$$

The resulting Mixed Integer Programming model is reported in the following:

$$\text{Max}\,\mathit{profit} \tag{1}$$

$$\text{s.t.} \sum_{j \ in \ I0} X_{ijk} = \sum_{j \ in \ I0} X_{jik} \ \forall i \in I, \ \forall k \in K \tag{2}$$

$$\sum_{j \ in \ I0} X_{0jk} \leq 1 \ \forall k \in K \tag{3}$$

$$\sum_{j \ in \ I0} X_{ijk} = Y_{ik} \ \forall i \in I, \ \forall k \in K \tag{4}$$

$$\sum_{j \ in \ I0} \sum_{k \ in \ K} X_{ijk} = 1 \ \forall i \in I^c \tag{5}$$

$$\sum_{j \ in \ I0} \sum_{k \ in \ K} X_{ijk} \leq 1 \ \forall i \in I^O \tag{6}$$

$$T_j \geq T_i + t_i + \widetilde{t_{ij}}\text{-}24(1\text{-}\sum_{k \ in \ K} X_{ijk} \tag{7}$$

$$T_i \geq e_i \quad \forall i \in I \tag{8}$$

$$T_i \leq l_i \quad \forall i \in I \tag{9}$$

$$Y_{ik} \leq \varphi_{ik} \ \forall i \in I, \ \forall k \in K \tag{10}$$

The objective function, consisting into maximizing the total profit given by the collected revenue minus the costs, is reported in (1). Constraints (2) ensure route continuity for each vehicle. Constraints (3) state that a vehicle can perform a single trip (which can be composed by an arbitrary number of tasks). A trip must be performed by the same vehicle to which it has been assigned (constraints (4)). Constraints (5) guarantee that compulsory tasks are performed, while it is not mandatory to perform optional tasks (constraint (6)). The starting time of each task is tracked by constraints (7), which must be included in the prefixed time window associated to the task, as imposed by constraints (8) and (9). Finally, a task can be executed by a vehicle only if they are compatible (constraints (10)). The emissions related to the optimal solution of this model, can be computed ex-post. If we want to minimize emission instead of maximizing the company profit, it is sufficient to substitute (1) with (11).

$$\min emissions \tag{11}$$

Similarly, to the previous case, the profit associated to the solution which minimize emissions can be computed ex-post.

3. Case Study

The model is applied for the case of the transportation service connecting the mainland ports of Milazzo and Vibo Valentia with the Aeolian islands in the Tyrrhenian Sea. The transportation company is provided by 13 hydrofoils and 4 monohulls connecting the mainland ports with all the 7 ports of the Aeolian islands. The main characteristics of each hydrofoil in terms of name, type, capacity, construction year, consumption and CO_2 emissions for mile are reported in Table 1.

The functional landings for the performance of the public service are the ports of: Milazzo, Vulcano Lipari, Salina-Rinella, Panarea, Ginostra-Stromboli, Filicudi, Alicudi and Vibo Valentia as shows in Fig. 1.

The main characteristics of each landing are reported in the following Table 2 (www.regione.sicilia.it):

The distance matrix reported in Table 3 is defined on the basis of the distances determined by the harbor master's office and on the basis of the distances between ports in the Sicilian region.

3.1. Regional requirements

Due to the territorial continuity of the minor islands of Sicily, the minimum requirement that must be guaranteed by the public maritime transport service of passengers consists of the following 7 lines (www.regione.sicilia.it):

1 Milazzo-Vulcano-Lipari- S.M. Salina-Rinella e v.v.
2 Lipari- S.M. Salina-Rinella e v.v.
3 Milazzo-Vulcano-Lipari- S.M. Salina-Panarea-Ginostra-Stromboli e v. v.
4 Milazzo-Vulcano-Lipari-Rinella-Filicudi-Alicudi e v.v.
5 Lipari-Rinella-Filicudi-Alicudi e v.v.
6 Milazzo-Vulcano-Lipari e v.v.
7 Vibo Valentia-Stromboli e v.v.

The vessels must have a minimum capacity of 200 passengers. The Table 4 shows the total number of weekly berths for each port involved in the regional supplementary maritime services for the Aeolian Islands in the different seasonality (high, medium, low).

In Tables 5, 6 and 7 the minimum quantification of the connection service to be implemented, in number of trips per week (gone and return) and nautical miles to be covered per line and season, is reported.

The Navigation Company is obliged to apply for the first regulatory period tariffs not exceeding those described for each season in the Table 8 and 9 (www.regione.sicilia.it).

3.2. Computational analyses

We performed different analyses. In the first one, we considered the high season weekly schedule. We address a daily schedule in which we supposed to be mandatory all the tasks, even those for which the

Table 1
Vessels characteristics

#	Name	Type	Capacity [n.passengers]	Construction year	Consumption [kg/mile]	CO_2 emission [kg/mile]
1	CARMINE	hydrofoils	215	2019	25.551	317.803338
2	AMMARÌ	hydrofoils	233	2015	23.38	290.80044
3	NATALIE M	hydrofoils	207	2002	21.36765	265.7708307
4	MIRELLA MORACE	hydrofoils	220	2006	22.2778	277.0912764
5	EDUARDO M	hydrofoils	207	1996	21.41775	266.3939745
6	ETTORE M	hydrofoils	204	2003	22.41975	278.8568505
7	ADRIANA M	hydrofoils	207	1999	21.58475	268.4711205
8	TIZIANO	hydrofoils	200	1994	18.2364	226.8243432
9	PLATONE	hydrofoils	218	2006	20.8583	259.4355354
10	ESCHILO	hydrofoils	222	2005	21.51795	267.6402621
11	ERACLIDE	hydrofoils	220	2005	23.547	292.877586
12	CALYPSO	hydrofoils	220	2005	22.6786	282.0764268
13	ANTIOCO	hydrofoils	220	2005	22.16925	275.7411315
14	EMMA M	monohulls	200	2014	22.2611	276.8835618
15	CARLOTTA M	monohulls	200	2011	24.64085	306.4828923
16	MARCO M	monohulls	200	2012	23.10445	287.3731491
17	SOFIA M	monohulls	200	2010	23.714	294.954732

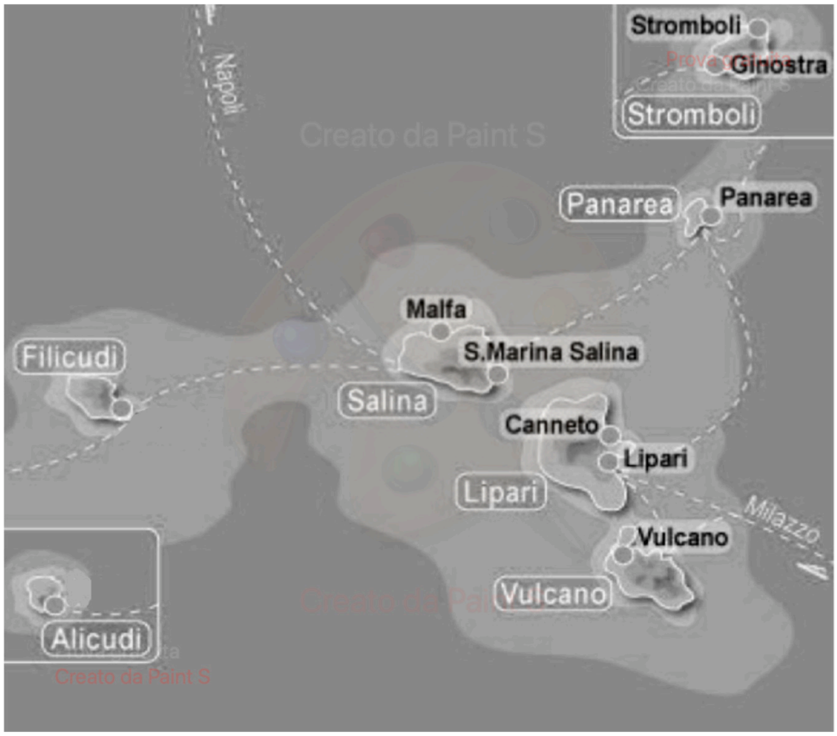

Fig. 1. Main ports of Aeolian Islands

Table 2
Landings characteristics

Port	
Milazzo	Rizzo Wharf - North Approach:Length mt 35; Draught: mt 9 Rizzo Wharf - South Approach:Length mt 38; Draught: mt 8
Lipari	Length mt 250; Draught: mt 10
Panarea	Length mt 106; Draught: mt 6.2
Stromboli	Length mt 85; Draught: mt 7
Ginostra	Length mt 98; Draught: mt 5
Filicudi	Length mt 67; Draught: mt 6.2
Alicudi	Length mt 48; Draught: mt 7
Salina	Length mt 230; Draught: mt 9
Rinella	Length mt 85; Draught: mt 4.5
Vulcano	Length mt 234; Draught: mt 11.6
ViboValentia	Length mt 67; Draught: mt 6.2

mandatory minimum number of days per week on which they have to be executed, is lower than 7. The total amount of tasks to be scheduled is 18 (i.e. all the filled cells of Table 4) and the number of available vessels is 17 with different emissions/mile, costs/mile and capacity, as reported in Table 1. We compared the optimal solution obtained maximizing the profit with the one obtained minimizing the emissions. The maximum profit achievable is equal to 31,505 Euro and the correspondent amount of emissions is 9,674 kg. Minimizing the emissions, is possible to decrease this value to 8,594 kg, but the profit will decrease too to 29,337. This means that to reach the highest level of sustainability the company must accept a loss of 6.88% of its profits. On the other hand, the solution which guarantee the maximum profit imply a 11.11% increment of emissions, which is high but not dramatic. Thus, our conclusion is that the two objectives are not completely in contrast and

Table 4
total number of weekly berths for the different seasons

Port	High (1 june-30 september)	Medium (1 april-31 may and 1-31 october)	Low (1 november-31 march)
Milazzo	43	39	34
Lipari	65	96	92
Panarea	24	22	18
Stromboli	14	11	9
Ginostra	24	22	18
Filicudi	6	10	10
Alicudi	3	5	5
Salina	38	104	100
Rinella	10	41	41
Vulcano	86	78	74
ViboValentia	2	0	0

Table 3
Distances matrix [miles]

	Milazzo	Lipari	Panarea	Stromboli	Ginostra	Filicudi	Alicudi	Salina	Rinella	Vulcano	ViboValentia
Milazzo		22	26.5	35.5	35	30.5	48	28	29	19.5	55
Lipari	22		11.5	25.5	22.5	21.5	30.5	10	10.5	4	57
Panarea	26.5	11.5		15	10.5	24	35	11	14	15	55.5
Stromboli	35.5	25.5	15		4.5	36	45	23.5	31	28.5	44
Ginostra	35	22.5	10.4	4.5		32	41.5	20.5	24	25	45
Filicudi	30.5	21.5	24	36	32		12.5	15.5	12	21	75
Alicudi	48	30.5	35	45	41.5	12.5		26	22	30	85
Salina	28	10	11	23.5	20.5	15.5	26		5	12	61
Rinella	29	10.5	14	31	24	12	22	5		11.5	83
Vulcano	19.5	4	15	28.5	25	21	30	12	11.5		59.5
ViboValentia	55	57	55.5	44	45	75	85	61	83	59.5	

Table 5
Level of service in the high season

Time Slot	7am-9am g	7am-9am r	9am-12.30am g	9am-12.30am r	12.30am-2.30pm g	12.30am-2.30pm r	2.30pm-5pm g	2.30pm-5pm r	5pm-7pm g	5pm-7pm r	After 7pm g	After 7pm r	Tot	Miles
Milazzo-Vulcano-Lipari- S.M. Salina-Rinella		7											7	4,697
Lipari- S.M. Salina-Rinella	7												7	1,830
Milazzo-Vulcano-Lipari- S.M. Salina-Panarea-Ginostra-Stromboli			7	5	5					7			24	24,888
Milazzo-Vulcano-Lipari-Rinella-Filicudi-Alicudi				3									3	3,059
Lipari-Rinella-Filicudi-Alicudi	3												3	1,830
Milazzo-Vulcano-Lipari			7	7	7	7	7		7	7	3		52	21,298
Vibo Valentia-Stromboli				2			2						4	2,921

Table 6
Level of service in the medium season

Time Slot	7am-9am g	7am-9am r	9am-12.30am g	9am-12.30am r	12.30am-2.30pm g	12.30am-2.30pm r	2.30pm-5pm g	2.30pm-5pm r	5pm-7pm g	5pm-7pm r	After 7pm g	After 7pm r	Tot	Miles
Milazzo-Vulcano-Lipari- S.M. Salina-Rinella			7	14			14			7	7		49	24,794
Lipari- S.M. Salina-Rinella	13	6								7		7	33	6,506
Milazzo-Vulcano-Lipari- S.M. Salina-Panarea-Ginostra-Stromboli			7			7	4			4			22	17,204
Lipari-Rinella-Filicudi-Alicudi	5	5											10	4,600
Milazzo-Vulcano-Lipari				7									7	2,162

Table 7
Level of service in the low season

Time Slot	7am-9am g	7am-9am r	9am-12.30am g	9am-12.30am r	12.30am-2.30pm g	12.30am-2.30pm r	2.30pm-5pm g	2.30pm-5pm r	5pm-7pm g	5pm-7pm r	After 7pm g	After 7pm r	Tot	Miles
Milazzo-Vulcano-Lipari- S.M. Salina-Rinella			7	14			7	7		7	7		49	40,695
Lipari- S.M. Salina-Rinella	13	6								7		7	33	10,678
Milazzo-Vulcano-Lipari- S.M. Salina-Panarea-Ginostra-Stromboli			7	7	2					2			18	23,103
Lipari-Rinella-Filicudi-Alicudi	5	5											10	7,550
Milazzo-Vulcano-Lipari				7									7	3,549

even following an economic goal, i.e., the profit maximization, it is possible to achieve a quite sustainable solution. The other insight we can derive is that, if the Sicilian Region would cover the loss of profit for the company, then the sustainability goal can be achieved with a reasonably small economic effort for the collectivity.

The vehicles used in the optimal solution, the mileage covered by each vehicle, the correspondent emissions, and the capacity of each vehicle, when maximizing profit and minimizing emissions, are reported in Tables 10 and 11 respectively.

As expected, to maximize the profit, the model selects vehicles with

Table 8
Maximum tariffs for the medium and low seasons (data in €)

		Regular		Resident	
		adults	children	adults	children
MILAZZO	Vulcano	12.64	8.36	4.32	2.55
	Lipari	13.36	8.73	4.59	2.68
	Rinella	15.68	10.05	5.45	3.14
	Salina	15.27	9.73	5.32	3.05
	Panarea	15.27	9.73	5.32	3.05
	Ginostra	19.23	11.77	7.64	4.23
	Stromboli	18.50	11.41	6.64	3.73
VULCANO	Lipari	5.00	4.00	1.59	1.18
	Rinella	8.91	6.09	2.95	1.91
	Salina	8.91	6.09	3.05	1.91
	Panarea	9.45	6.36	3.32	2.05
	Ginostra	15.73	9.91	6.23	3.50
	Stromboli	16.41	10.41	5.82	3.32
LIPARI	Rinella	8.27	5.73	2.86	1.82
	Filicudi	14.36	9.27	4.59	2.68
	Alicudi	17.14	10.77	5.91	3.36
	Salina	7.82	5.55	2.59	1.68
	Panarea	8.91	6.09	3.05	1.91
	Ginostra	15.27	9.73	5.95	3.36
	Stromboli	15.27	9.73	5.32	3.05
RINELLA	Filicudi	9.45	6.36	3.05	1.91
	Alicudi	14.36	9.27	4.59	2.68
FILICUDI	Alicudi	10.09	6.64	3.32	2.05
SALINA	Panarea	8.27	5.73	2.86	1.82
	Ginostra	13.82	9.00	5.50	3.14
	Stromboli	14.09	9.09	4.77	2.77
	Rinella	5.73	4.36	1.86	1.32
PANAREA	Ginostra	9.45	6.36	4.05	2.41
	Stromboli	9.45	6.36	3.32	2.05

Table 9
Maximum tariffs for the high season (data in €)

		Regular		Resident	
		adults	children	adults	children
MILAZZO	Vulcano	13.64	8.91	4.32	2.55
	Lipari	14.36	9.27	4.59	2.68
	Rinella	15.95	10.14	5.45	2.36
	Filicudi	20.23	12.32	7.09	3.18
	Alicudi	25.18	15.55	8.55	4.68
	Salina	15.95	10.14	5.45	2.36
	Panarea	16.18	10.18	5.32	3.05
	Ginostra	19.05	11.68	6.64	2.95
	Stromboli	19.05	11.68	6.64	2.95
VULCANO	Lipari	5.27	4.18	1.59	1.18
	Rinella	9.45	6.36	3.05	1.91
	Filicudi	13.64	8.91	4.32	2.55
	Alicudi	16.68	10.50	5.73	3.27
	Salina	9.45	6.36	3.05	1.91
	Panarea	10.09	6.64	3.32	2.05
	Ginostra	17.59	10.95	5.82	3.32
	Stromboli	17.59	10.95	5.82	3.32
LIPARI	Rinella	8.73	6.00	2.86	1.82
	Filicudi	14.36	9.27	4.59	2.68
	Alicudi	17.14	10.77	5.91	3.36
	Salina	8.00	5.64	2.59	1.68
	Panarea	9.45	6.36	3.05	1.91
	Ginostra	16.18	10.18	5.32	1.68
	Stromboli	16.18	10.18	5.32	3.05
RINELLA	Filicudi	9.45	6.36	3.05	1.91
	Alicudi	14.36	9.27	4.59	2.68
FILICUDI	Alicudi	10.09	6.64	3.32	2.05
SALINA	Panarea	8.73	6.00	2.86	1.82
	Ginostra	14.82	9.45	4.77	2.77
	Stromboli	14.82	9.45	4.77	2.77
	Rinella	5.91	4.45	1.86	1.32
PANAREA	Ginostra	10.09	6.64	3.32	2.05
	Stromboli	10.09	6.64	3.32	2.05
VIBO VALENTIA	Stromboli	23.64	14.55	7.91	4.41

larger capacity, while to minimize the emissions, low-emissions vehicles are preferred. While vehicle 9 shows a high capacity associated to moderate emissions (and therefore it is selected in both solutions), vehicle 2 has a very large capacity but very high emissions too and for this reason is discarded in the most sustainable solution. Vehicle 10 with its large capacity is convenient to maximize profit, but when the goal is to reduce emissions, it is substituted by the more sustainable vehicle 3, which has slightly lower emissions, but a smaller capacity. A solution to keep high profits and improve sustainability, would be to substitute vehicle 2 and 10 with newer and more sustainable vehicles holding the same high capacity.

The second analysis was conducted based on market analysis using traffic data collected by the competent Port System Authorities, the Sicilian Region, and Liberty Lines jsc. The purpose was to provide evaluation elements for identifying additional routes beyond the mandatory ones regulated by the agreement between the Sicilian Region and Liberty Lines jsc, which operates under the public service obligation regime. To achieve this, an overall assessment of the traffic generated on the maritime routes ensuring territorial continuity between Sicily and the Aeolian Islands, as regulated by the agreement, was conducted for the 2021-2022 biennium. An overview of the connections was performed, considering existing public service needs and market conditions. Initially, the main summary information obtained from the analysis of demand and supply data on the routes covered by the agreement was examined, providing a general review of market characteristics. Subsequently, specific elements of comparison were identified, along with observations regarding potential service demand. In summary, the following activities were carried out:

a) Definition of public service needs.
b) Market verification, aimed at determining the presence of a total or partial economic interest of the operator in providing the service in a free market without compensation.

Table 10
Vehicles usage in the optimal solution when the objective is the profit maximization.

VEHICLE	MILEAGE	EMISSIONS (C02kg/mile)	CAPACITY
2	310.8	23.38	233
9	134.4	20.86	218
10	221.2	21.52	222

Table 11
Vehicles usage in the optimal solution when the objective is the emissions minimization.

VEHICLE	MILEAGE	EMISSIONS (C02kg/mile)	CAPACITY
3	148.4	21.37	207
8	324.8	18.24	200
9	193.2	20.86	218

c) On-desk analysis of current and potential demand, involving direct investigations based on available data and information, including input from transport service users subject to analysis and associations.

The objective was to identify one or more origin-destination relationships that require maritime transport services, determine the time slots of interest to users during different periods of the year, week, and day, and ascertain the corresponding maximum willingness to pay.

a) Consultation focused on market verification, providing the shipping company with the results obtained from the analyses described in the previous point (c).

The market analysis allowed the identification of a set of additional, potentially attractive, tasks.

In Table 12 we report a resume of the mandatory tasks (in black) and additional optional tasks (in red). Those tasks are all concentrated on the line Milazzo-Vulcano-Lipari which is the one with highest passenger traffic. The additional tasks are all considered not mandatory. We assume that all the additional tasks, if performed, would have enough demand to fill up the vehicle's capacity.

Results indicate that it is convenient to perform all the additional tasks and that the total profit will increase to 42,642 versus 31,505 achievable by performing only mandatory tasks. This outcome was expected, in fact, the operating costs of tasks are always lower than the profit achievable which means that it is always convenient to perform optional tasks as long as there are enough vehicles available.

However, while only 3 vehicles, (2,9 and 10) were needed to perform only mandatory tasks, adding the optional ones would require the usage of an additional vehicle (8), which would become not available for other services, on other archipelagoes, the company would like to perform. Therefore, we decided to make another simulation, imposing that the number of vehicles used must be lower or equal than 3. Results show that, even without adding an extra vehicle, it is possible to strongly increase the total profit by performing optional tasks. In fact, it is possible to achieve a profit of 39,598, by adding 9 of the 12 optional tasks. In particular, the services omitted are the two to be carried out between 12:30 am and 2:30 pm (in both directions), plus two of the three from Lipari to Milazzo, planned between 2:30 pm and 5 pm, period in which only one additional service is performed.

Finally, the third analysis takes into account the significant push towards decarbonization that is occurring both globally and by the European Union, which has highly impactful effects on the shipping sector as well. Driven by increasingly stringent environmental regulations set by both the International Maritime Organization (IMO) and the European Union (EU), shipowners are considering the use of green solutions offered by technology, which are increasingly focusing on the use of hybrid propulsion. This system combines the use of technologies to reduce emissions. The concept of electric propulsion is not new, as it originated approximately a century ago. Since the 1980s and 1990s, electric power has been used as a propulsion source on passenger transport vessels. However, this system is not environmentally sustainable, as electric power is generated by diesel generators connected to alternators. On the other hand, the use of batteries for propulsion in the maritime field presents significant technical challenges. Currently, the available technology is not yet capable of creating fully electric engines for ships that can cover an entire voyage. Only for short-range navigation (in lagoons, lakes, or for short marine routes) is it possible to have fully electric battery-powered engines. At present, there are two types of solutions: hybrid generation and hybrid propulsion. In the former case, diesel engines and alternators are used, supplemented by batteries capable of storing the energy generated during navigation and ensuring emission-free operation, with all onboard services functioning, when the ship is in port. As for hybrid propulsion, it is achieved by coupling traditional engines with electric motors. In modern electric propulsion systems, energy generation is concentrated in a single power plant that provides for the energy needs of both propulsion and non-propulsive users. In this case, the benefits are not limited to port stops but also enable emission-free navigation segments, such as zero-emission mooring maneuvers. In the third analysis, we address a scenario in which the most inefficient vessels are replaced with 10 hybrid propulsion ships with a standard capacity of 200 passengers. These vessels utilize electric motors for docking operations within the port, while the diesel propulsion engine is used for navigation once the vessel is outside the port area. Furthermore, as these internal combustion engines are built with the latest technologies, they offer lower fuel consumption and emissions compared to previous models, providing advantages both economically and in terms of sustainability.

For the analysis, a vessel's useful life of 30 years was considered, with an estimated investment cost inclusive of capitalization costs required to make the vessel suitable for service over the 30 years. Since the investment cost is significant, it was assumed that the shipping company would seek a bank loan with an interest rate of 3%, in line with the current level of interest rates. We estimate that the daily rate of purchasing cost, D, is equal to 978 Euros, while the emissions, in terms of CO_2/kg/mile are considered equal to 7.19 and the cost per mile is 6.87 Euro.

To consider the depreciation cost in the computation of the total cost, we redefine the profit as:

$$\text{profit} = \sum_{i \text{ in } I} \sum_{k \text{ in } K} (p_{ik} Y_{ik} - c_{ik} Y_{ik}) - \sum_{i \text{ in } I0} \sum_{j \text{ in } I0} \sum_{k \text{ in } K} \widetilde{c_{ijk}} X_{ijk} - \sum_{j \text{ in } I0} \sum_{k \text{ in } K^E} D X_{0jk}$$

where K^E is the set of electric vessels. The last term indicates the purchasing costs daily rate.

With the new, more sustainable fleet, it is possible to achieve a daily profit of 32,125 Euros which is significantly higher than those obtainable with the totally diesel propelled fleet, 31,505 Euros. In fact, the high purchasing costs are completely balanced by a significantly lower sailing cost, which yields to an extra profit. Furthermore, also a relevant daily emissions reduction can be achieved, passing from 9,674 to 8,875. This way, introducing hybrid vehicles would yield a twofold benefit both from an economics and a sustainability point of view.

Moreover, if instead of maximizing profit we minimize emissions, it is possible to achieve a strongly lower daily emissions level, 7,195 kg/

Table 12
Resume of mandatory and optional tasks considered.

Time Slot	7am-9am g	7am-9am r	9am-12.30am g	9am-12.30am r	12.30am-2.30pm g	12.30am-2.30pm r	2.30pm-5pm g	2.30pm-5pm r	5pm-7pm g	5pm-7pm r	After 7pm g	After 7pm r
Milazzo-Vulcano-Lipari- S. M. Salina-Rinella		1										
Lipari- S.M. Salina-Rinella	1											
Milazzo-Vulcano-Lipari- S. M. Salina-Panarea-Ginostra-Stromboli			1	1	1					1		
Milazzo-Vulcano-Lipari-Rinella-Filicudi-Alicudi				1								
Lipari-Rinella-Filicudi-Alicudi	1											
Milazzo-Vulcano-Lipari		1	1+2	1+2	1+1	1+1	1+3		1+2	1	1	
Vibo Valentia-Stromboli				1			1					

CO_2, with a profit which is only slightly lower (30,929 instead of 31,505) than the highest profit obtainable with a full diesel propelled fleet.

This means that, the cost of being sustainable, in terms of loss of profit, is quite limited and represents only the 1.83% of the total profit. Thus, we think that the Sicilian region could easily effort these costs, offering small incentives to the company, to offer a more sustainable service without reducing its profit. Therefore, the adoption of a hybrid fleet is viable and convenient for both the company and the community.

4. Conclusions

This research introduces the vehicle scheduling problem with optional tasks and vehicle dependent profits. The motivation of this work comes from a real application concerning ferry services operated between the two ports of Milazzo and Vibo Valentia and the Aeolian islands.

In this context, the company must operate a set of predetermined services, each one of which, within a specific time-window, provided by the regional government. Beside these mandatory tasks, the company can choose to operate additional services to gain an extra profit. The profit is vehicle-dependent since it is proportional to the number of passengers the vehicle can carry.

Three analyses were formed and modeled. The first one aims to compare the optimal solution obtainable by maximizing the profit with the one obtainable by minimizing the emissions.

To reach the highest level of sustainability the company must accept a loss of 6.88% of its profits. On the other hand, the solution which guarantee the maximum profit imply a 11.11% increment of emissions, which is high but not dramatic. Thus, our conclusion is that the two objectives are not completely in contrast and even pursuing an economic goal, such as the profit maximization, it is possible to achieve a quite sustainable solution. Moreover, the regional government could decide to cover the loss of profit for the company in order to provide a full sustainable schedule, for a relatively small cost. The second analysis show that the company can significantly increase its profit by performing additional optional tasks, better exploiting its fleet. The advantage in this case is twofold. On one hand, the company can achieve a higher profit. On the other hand, the customers can experience a better service with a significantly increment of the frequency of most attractive services.

The third analysis concerns the exploitation of new-generation hybrid vessels with limited emissions. Such vehicles are more sustainable than traditional diesel-propelled ones but require a large purchasing investment, since their price is still very high. Through experimental results we showed that substituting a part of the fleet with these new vehicles, will strongly reduce the emissions at the price of a small profit decrease (only the 1.83% of the total profit), which can be easily covered by the regional government.

The model we designed is general and does not describe only this specific maritime application but can applied to solve all the scheduling problems in which a set of mandatory tasks must be performed, while a set of additional optional tasks can be established to increase the company profit. This could apply for bus companies as well as for airlines. The novelty of the model with respect to the current literature, is twofold. Firstly, we consider both mandatory and optional services. Secondly, we consider a vehicle-dependent profit.

The limitation of this approach is that to correctly estimate the extra profit achievable with optional tasks, and to identify the most promising tasks, we need detailed data on customers demand which are not always available for all applications.

Future developments in this field may concern the integration of vessel scheduling with drivers/crew scheduling, which has never been addressed in the context of mandatory and optional tasks. Furthermore, even if for ferry lines application the number of daily services is somehow limited and the decision problem can be easily handled by exact models, the design of heuristics algorithms could be needed to solve larger problems arising in different context such as bus lines scheduling.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used are reported in the article

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