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The Optimal Arrangement of Boats in a Coastal Maritime Passenger Lines System Using Graph Theory

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Abstract: This paper presents research in the field of optimization in maritime passenger traffic that can ensure the long-term sustainability of coastal maritime passenger lines system. For the purpose of the research contained in this paper, it has been hypothesized that the optimal arrangement of boats within a coastal maritime passenger lines system will reduce the consumption of propulsion energy, the emission of harmful gasses and operating costs. The aim of this paper is to present an efficient algorithm for a reduction in propulsion energy consumption in coastal maritime passenger lines systems by reassigning boats to lines that they service. The problem is modeled using a bipartite graph and the solution is obtained by searching for optimal matching using Edmonds' algorithm. The authors apply, for the first time, Edmonds' algorithm to the problems of the optimization of assignments of boats to lines. The research results were confirmed by tests on a representative example. The optimization results on only 10 ships in the given example show yearly savings of 91,097.30 L of fuel (lowering costs by EUR 69,233.95) and reducing CO_2 by 243.59 tons, which proves that this algorithm found a much more efficient arrangement that could result in a significant reduction in propulsion energy consumption, thus providing economic and ecological benefits.

Keywords: maritime passenger transport; optimization; long-term sustainability; propulsion energy consumption; ecology

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1. Introduction

Maritime passenger transport is one of the most important segments of maritime transport. One part of maritime passenger transport is a coastal maritime passenger lines system managed by the state, as a basic prerequisite for the sustainable development of any maritime country with an indented coastline. Without safe and effective traffic connections between islands and the mainland, it is not possible to develop economic and social activities, which has an impact on the population, the standard of living, the birth rate and the development of islands.

The system of transport connections between islands and the mainland and between the islands themselves depends on traditions, standards, the legal framework and transport and maritime policy. Maritime transport policy, as part of transport policy, should ensure the effective implementation of a maritime transport system. The continuous development of the transport system in terms of technical, technological, organizational, economic, social, environmental and legal aspects can be achieved through an optimal transport policy [1].

There is no unique approach to this challenging and important issue, but the goal of all maritime states is the same—to create a sustainable coastal maritime passenger lines system, which can be achieved by rationalizing the system according to the optimal use of available resources while maintaining the level of quality. The main hypothesis of this paper is that the current state of coastal maritime passenger lines system can be improved through the use of mathematical algorithms.

This paper contains a model of the optimal arrangement of boats in a coastal maritime passenger lines system from the aspect of the consumption of propulsion energy. The model created optimally matches boats and boat lines in terms of energy consumption using the Edmonds' algorithm and graph theory methods. This arrangement of boats can improve the long-term sustainability of the coastal maritime passenger lines system.

The main contribution of this paper is the introduction of Edmonds' algorithm to problems of the optimization of the assignment of boats to lines. To our knowledge, this methodology has not been used to solve such problems. In the literature, analogous problems have been analyzed using mixed-integer programming [2–4]. However, no polynomial algorithm for mixed-integer programming is known which limits the number of boats that can be observed. There is no such limitation for Edmonds' algorithm.

The proposed model is tested on the example of the Republic of Croatia, whose coastal indentation coefficient is 11.1 [5]. Also, the Croatian archipelago is the second largest archipelago in the Mediterranean, with 3.3% of the total population of the Republic of Croatia living on its islands, according to the latest census from 2021 [6]. Due to the highly indented coastline, a considerable number of inhabited islands and the well-developed transportation system between the islands and the mainland, as well as between the islands themselves, the Republic of Croatia is a highly representative example for testing a model of the optimal arrangement of boats in a coastal maritime passenger lines system from the aspect of propulsion energy consumption.

2. Literature Review

Numerous scientists have researched the importance of maritime passenger traffic from different points of view. For example, Gračan et al. (2022) [7] pointed out that passenger maritime transport is one of the most important segments of maritime transport according to technological, economic and organizational criteria. They pointed out that maritime passenger transport is influenced by numerous trends and is also a driver of development. However, the key lies in achieving sustainability in relation to development. Mišura et al. (2020) [8] conducted a scientific study on the influence of transport connections between the islands and the mainland and between the islands themselves on demographic outcomes. They concluded that these transport connections have a positive impact on economic and social activities, which creates the conditions for the sustainable development of islands and increases the quality of life on the islands, which is also confirmed by the growth of the islands' population on the bridged islands and the decrease in the number of inhabitants on the small and unbridged islands. The aim is to ensure the sustainable development of maritime passenger traffic in a high-quality manner, involving all stakeholders with good knowledge of the state of the system and its potential.

Because the main objective of this thesis is to contribute to the optimization of boat arrangement in a coastal maritime passenger lines system in order to achieve long-term sustainability, existing scientific research on this topic was analyzed.

Iksan et al. (2024) [9] researched the optimization of routes in maritime passenger transport with the aim of creating more efficient and comfortable passenger transport. The authors concluded that it is necessary to use different optimization methods to achieve the specified parameters. Barone et al. (2021) [10] researched the optimization of maritime passenger transport from the perspective of reducing pollution from modern cruise ships using dynamic simulations in the design and optimization of energy efficiency. However, optimization research in other types of shipping is more pronounced, so Mulder et al. (2016) [11] concluded that the optimization process in liner shipping can be achieved by shorter navigation routes and avoiding challenging sea routes. Tran et al. (2013) [12] reviewed the scientific literature on optimization in liner shipping in their research and concluded that the topic of optimization in liner shipping has long been of interest to many scientists and that the aim of most research is to show that optimization reduces costs and negative impacts on the environment. The authors emphasized the importance of shipping network design. In his paper, Noshokaty (2021) [13] presented a modified model for the design of sea routes and schedules in liner shipping in terms of transportation times in order to achieve the highest possible gross profit per day. Research has shown that the presented stochastic methods achieve higher gross profit for a given cargo boat, and this method suggests the speed of navigation for the timely delivery of goods. Martinez-Lopez et al. (2020) [14] researched a tool to support the development of intermodal transport, including maritime transport as much as possible, in order to achieve optimal solutions for container fleets. The model presented takes several criteria into account and leads to lower costs and reduced environmental impact. Fan et al. (2019) [15] researched the optimization of costs and pollution in cargo transportation by tramp ships, which can be achieved through optimal arrangement and sailing speed. The authors Giavarina dos Santos et al. (2024) [16] used mixed-integer linear programming to create a model that creates optimal boat routes for cargo ships to reduce operating costs, transportation time and delays. Buonomano et al. (2023) [17] researched ways to improve sustainability in the maritime sector through the energy design and optimization of large ships using information modeling and dynamic simulations. The research by Wang et al. (2012) [18] contains a mixed-integer non-linear programming model optimizing the navigation speed of container boats. The scientific paper by Wang et al. (2013) [19] gave a critical review of the literature on mathematical methods in boat fuel consumption optimization, as fuel consumption and the emission of harmful gasses into the atmosphere are of critical importance for shipping companies. The authors investigated several methods that can serve as an aid in optimizing speed, i.e., fuel consumption, reducing pollutant emissions and planning port and transport operations. Xia et al. (2021) [2] researched the optimal use of different types of boats in terms of efficiency, with a focus on reducing carbon emissions in ports. In the work of Santos et al. (2023) [20], a two-stage stochastic programming algorithm is presented to achieve the optimization of how the movement of a supply boat is planned, depending on uncertain demand and uncertain weather conditions.

The concept of optimization in maritime transport is most strongly represented in research on liner shipping and on transport and logistics processes in shipping. Many optimization methods and models have been applied to the creation of itineraries and boat schedules, the determination of optimal travel speed and the energy efficiency of boats. Optimization is mainly carried out to reduce business costs, propulsion energy consumption and emissions of harmful gasses into the atmosphere, provided that the agreed deadlines are met and the shipping companies make as much profit as possible. It can be concluded that the research of ways of optimization in maritime passenger transport is an interesting research topic with significant possibilities.

3. The Objective Function of the Optimal Arrangement of Boats in the Coastal Maritime Passenger Lines System from the Aspect of Propulsion Energy Consumption

There are great efforts to improve maritime transport and to optimize it under different aspects and using different methods. The literature on optimization in maritime transport is extensive. It should be noted that the concept of optimization is more present in scientific research on liner cargo shipping, so that the key elements are profitability, cost reduction and travel time. Optimization in maritime transport is approached from different points of view using different methods and criteria.

In this paper, fuel costs are considered to be the most important factor from an economic and ecological point of view. As a key factor, propulsion energy has the greatest influence on the emission of pollutants into the atmosphere and on the financial impact. The main goal is to develop a concept for the sustainable development of the coastal maritime passenger line system from an economic and ecological aspect of view. The concept of sustainable development can be defined as a way of managing and conserving natural resources with a focus on technological and institutional changes in order to achieve and maintain the satisfaction of human needs for current and future generations [21]. Reducing the consumption of propulsion energy, eliminating diesel fuel and switching to renewable energy sources will lead to a long-term sustainable system of coastal maritime passenger lines [1], making the optimization of the energy efficiency of boats increasingly attractive to all those who care about saving propulsion energy and reducing the emission of harmful gasses into the atmosphere [22].

3.1. Ecological Sustainability of Coastal Maritime Passenger Lines System

Maritime transport contributes to 2.5% of global pollutant emissions in the world emission of harmful gasses [23] and 3.3% of CO_2 emissions [10]. Efforts are being made to develop multimodal transport and green technologies in order to reduce or eliminate the emissions of harmful gasses into the atmosphere caused by maritime transport and to ensure long-term sustainability. Institutional requirements are increasing, with the International Maritime Organization (IMO) mandating its members to reduce CO_2 emissions by 70% by 2050, i.e., the complete elimination of CO_2 emissions [23]. Since its foundation, the International Maritime Organization (IMO) has adopted more than 50 international conventions regulating international shipping, 21 of which are directly related to the environment [24]. All regulations for maritime transport also apply to its subsystem—coastal maritime passenger transport.

Propulsion energy is an important factor in maritime transport and heavy diesel fuel is still used, which contains hydrocarbons and many other components the combustion products of which are harmful to the environment and human health [25]. Carbon dioxide (CO_2) emissions are by far the most significant of the harmful gas emissions resulting from the combustion of fuels [24]. The maritime transportation sector is constantly evolving and trying to achieve a higher level of system sustainability and better responses to the problem of pollution [26]. Efforts are aimed at increasing the energy efficiency of boats [24] in different ways, depending on the type of shipping and the service to be provided, with the aim of achieving environmental and economic acceptability. The environmental acceptability of the boat (environmentally reasonable approach) is becoming an important factor in shaping shipowners' business policies in light of environmental legislation that sets new requirements and costs for shipowners [10].

Fuels and propulsion energy sources such as biofuels, hydrogen, ammonia or electricity are increasingly mentioned as alternatives to fossil fuels due to their lower negative impact on air pollution and greenhouse gas emissions [24]. This trend also applies to coastal liner maritime passenger traffic, but the idea of environmentally friendly energy sources has so far been characterized as uncertain, with a high price and low efficiency [27], so that it is primarily necessary to optimize the available resources from an ecological point of view.

3.2. Economic Sustainability of Coastal Maritime Passenger Lines System

The cost of propulsion energy accounts for a significant proportion of the total cost of the boat and the maintenance of the boat's lines [28]. Almost 40% of the total cost is accounted for by voyage costs, and the cost of fuel or propulsion energy is its most sensitive part [26].

The increasing institutional requirements also have a direct impact on the rising financial costs of shipping companies and the state. The state especially feels the financial pressure of co-financed boat lines, which are common in coastal maritime passenger line system. On the other hand, meeting the requirements of the institutional framework places a financial burden on shipping companies as they have to change, adapt and invest in their facilities [1]. The introduction of new technologies and facilities requires financial investment and time [1]. Therefore, liquidity and the availability of capital can only be ensured through a well-thought-out financial policy, economically viable boat utilization, boat insurance, fleet renewal and the development and growth of shipping companies [26]. In addition, the increase in the cost of operating a coastal maritime passenger lines system places a burden on the users of the services—the island population and all other passengers. All stakeholders in the system (passengers, shipowners, shipping companies, the government and suppliers) are also feeling the effects of other financial disruptions from the environment, such as rising commodity and energy prices, as well as the global financial crisis. The solution lies in the rational use of existing resources in order to create the conditions for further investment and the reduction in energy consumption, while ensuring the quality of services and the harmonization of the interests of all stakeholders in coastal maritime passenger lines system [1].

The optimization of existing resources creates the conditions for investment in new technologies and the use of environmentally friendly energy sources, so that the ecological and economic sustainability of coastal maritime passenger transport can be taken into account [1].

4. Methodology

A suitable model to represent all possible assignments of boats to boat lines is a bipartite weighted graph. One set of vertices of this graph consists of all observed boats and the other of all observed boat lines. There is an edge between the boat and the boat line if this boat is suitable for maintaining this line. The weight of this edge is the function of the fuel consumption of the observed boat servicing the observed line. The details of determining the suitability of the boat to serve a particular line and the definition of this function are described in this section.

Once such a graph is created, one can search for maximum weighted matches using Edmonds' algorithm to obtain the optimal assignment of boats to lines (i.e., an assignment that requires the least fuel consumption). Interested readers are referred to the original paper [29]. The efficient implementation [30] and even the pseudocode of the algorithm can be found online [31].

So, the first step is to create the bipartite graph, i.e., to decide which boat is suitable for which line. The parameters considered are: speed, distance, timetable, capacity and the ability of the boat to maintain a specific boat line in terms of its design and technical characteristics.

Based on the above parameters, the pairing of boats and boat lines is made by experts in order to avoid the possible incompatibility of boats with certain boat lines. The expert opinion method is non-quantitative, which makes it adaptable to practical requirements [32]. In this case, an individual assessment method is used, where there is no mutual communication between the experts, but each expert works independently and the organizer then determines the average or joint assessment of the expert opinion by processing the individual assessments [32]. The experts must have a high level of knowledge and experience in the field of the required assessments. Scientific research has also shown in other scientific fields that it is extremely important that experts from a particular field are involved in the assessment and that there are at least three experts working independently of each other [33]. An odd number of experts should also be chosen because there may be a tie that would make it impossible to determine whether a particular boat corresponds to a particular boat line.

Based on the results of the expert opinion method, we set the edge that connects a boat and a boat line if the majority of the experts consider this boat suitable for this line. The weight of each edge will be defined as $M - f_{ij}$ (where M is a sufficiently large number) and f_{ij} is the consumption of fuel by the observed boat servicing line. Note that a large value of M (it is enough to use M as the sum of all values f_{ij} in the graph) forces Edmunds' algorithm to return perfect matching and the negative sign preceding f_{ij} reflects the fact that we want to minimize fuel consumption.

Let us present this model more formally. Let us denote the observed boats by $b_1, \ldots, b_n$ and the observed boat lines by $l_1, \ldots, l_n$. Let us denote by f_i the average consumption of fuel per nautical mile of boat travel b_j. Let d_j be the distance that a boat travels along the boat line l_j and let t_j be a weekly number of journeys on the line l_j; then, $f_{ij} = f_i \cdot d_j \cdot t_j$. Hence, Edmonds' algorithm finds optimal perfect matching M_G, i.e.,

$$M_G = \underset{m \in S}{\operatorname{argmin}} \left(\sum_{i=1}^{n} f_i d_{m(i)} t_{m(i)} \right) \quad (1)$$

where S is a set of all perfect matchings of the observed graph G.

The methods of discrete mathematics, algorithms and graph theory were primarily used in the design of the proposed model of the optimal arrangement of boats in terms of the energy consumption of propulsion systems. Discrete mathematics has a strong presence in computer science, making it pervasive in all fields, including transportation system analysis [34]. The use of algorithms can provide significant benefits to transportation systems, such as a reduction in traffic volume, increased safety and more efficient transit systems. On the other hand, the application of graph theory enables the simple modeling of complex problems, which is why it is widely used in various disciplines. The application of graph theory is important in the field of complex systems and networks, including transportation networks. In particular, the application of graphs and linear programming in the optimization of a problem [35] is highlighted, which indicates the correct choice of the method in the creation of a model of the optimal arrangement of boats in a coastal maritime passenger lines system from the aspect of propulsion energy consumption.

By applying the process of data modeling using the mathematical methods of algorithms and graph theory, a data model is formed that serves to represent the parts of the system and their mutual relationships. The data model in this work is a weighted graph in which the edges connect the corresponding boats with predefined lines and the edge weights are assigned depending on the selected parameters.

The model offers the simple selection of criteria, which makes it very clear and concrete and adaptable to different needs and requirements.

5. Model Testing

The benefits of this model are demonstrated by optimizing the use of boats in the Republic of Croatia. In the Republic of Croatia, the transport connections between the islands and the mainland and between the islands themselves are regulated by bridge connections and the coastal maritime passenger lines system with 51 state-run lines with a public service obligation (24 ferry lines, 16 speed boat lines and 11 classic boat lines), which are maintained by 13 shipping companies with 82 boats [36]. Ten of the 16 speed boat lines require a speed of 25 knots.

These lines and the boats that serve them are presented in Table 1.

Table 1. Speed boat lines (economic speed of 25 knots) and related boats—out of season.

Boat Line	Distance (in nm)	No. of Weekly Journeys	Minimal Capacity	Boat	Passenger Capacity	Fuel Consumption (L/nm)
Pula	88.3	1	250	BIŠOVO	325	30
Mali Lošinj	61.6	7	300	DUBRAVKA	316	27.7
Novalja	56.3	7	300	ADRIANA	332	30.5
Olib	44	7	300	PRINC ZADRA	301	27
Ist	25.5	8	250	SILBA	300	27.3
Žirje	15.6	12	100	MALI PRINC	200	14
Vis	29.6	7	250	KAROLINA	316	30.8
Jelsa	30	7	300	VIDA	304	29.3
Lastovo/Ubli 1	60.1	7	300	JUDITA	316	28.6
Lastovo/Ubli 2	21.8	7	200	NONA ANA	202	19

Source: Coastal Liner Services Agency, www.agencija-zolpp.hr, accessed on 30 September 2024.

In Table 1 and Figure 1, the boat lines are shown only by the name of the port of departure.

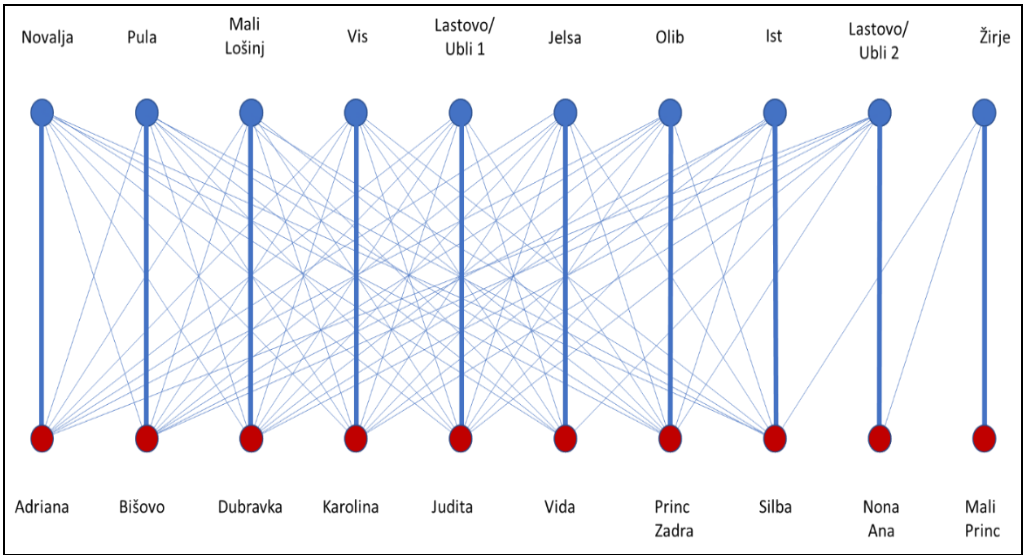

Figure 1. Connecting high-speed boats and speed boat lines—out of season.

The next step was to create a bipartite graph. For this purpose, three experts with extensive experience and knowledge were selected—the director of a public institution that classifies and certifies boats by law on behalf of the national maritime authorities, a long-standing coordinator of the largest shipping company in the Republic of Croatia on a particular waterway, a seaman and doctor of science in the field of transport and maritime engineering, and a long-standing head of the Service for Technical and Operational Affairs of the Regulatory Authority of the Republic of Croatia in coastal maritime passenger line systems. These shipping experts gave their opinions on the suitability of boats for a particular boat line according to their maritime, structural and technical characteristics and the characteristics of the ports.

Based on their opinions, a bipartite graph presented on the following Figure 1 is constructed.

In Figure 1, the edges in bold correspond to the actual assignments of boats and boat lines, the other lines correspond to all other possibilities.

It should be noted that there are functions between the set of boats and the set of boat lines, so the analysis of each individual boat is not very efficient and, in some more complex examples, where the number of boats would be increased to 50, it would be almost impossible (due to the number of combinations). Therefore, the application of Edmonds' algorithm is indeed advantageous. Indeed, the complexity of Edmonds' algorithm is equal to the number of edges and the number of vertices of the graph [31]. Some modifications of this algorithm can even reduce this complexity. Therefore, this algorithm can be easily applied to a very large number of boats (even thousands of boats).

The optimal assignment in this example can be represented by the following graph (Figure 2).

Table 2 presents the calculation of savings when this reassignment is applied.

Table 2. Representation of initial assignment and optimal assignment.

Boat Line	Distance (in nm)	Initial Assignment				Optimal Assignment			
		Boat	Number of Weekly Journeys	Fuel Consumption (L/nm)	Weekly Fuel Consumption (in l)	Boat	Number of Weekly Journeys	Fuel Consumption (l/nm)	Weekly Fuel Consumption (in l)
Pula	88.3	BIŠOVO	1	30	5298	KAROLINA	1	30.8	5439.28
MaliLošinj	61.6	DUBRAVKA	7	27.7	23,888.48	SILBA	7	27.3	23,543.52
Novalja	56.3	ADRIANA	7	30.5	24,040.1	DUBRAVKA	7	27.7	21,833.14
Olib	44	PRINC ZADRA	7	27	16,632	JUDITA	7	28.6	17,617.6
Ist	25.5	SILBA	8	27.3	11,138.4	BIŠOVO	8	30	12,240
Žirje	15.6	MALI PRINC	12	14	5241.6	MALI PRINC	12	14	5241.6
Vis	29.6	KAROLINA	7	30.8	12,763.52	ADRIANA	7	30.5	12,639.2
Jelsa	30	VIDA	7	29.3	12,306	VIDA	7	29.3	12,306
Lastovo/Ubli 1	60.1	JUDITA	7	28.6	24,064.04	PRINC ZADRA	7	27	22,717.8
Lastovo/Ubli 2	21.8	NONA ANA	7	19	5798.8	NONA ANA	7	19	5798.8
total					141,170.94				139,376.94

Source: Authors.

Table 2 shows a saving of 1794 L in the out-of-season period.

The model test leads to lower propulsion energy consumption, which also means lower costs. The lower consumption leads to lower emissions of greenhouse gasses, especially CO_2, the most common greenhouse gas in maritime transport [37]. The entire maritime transport sector is an important source of CO_2 emissions. CO_2 emissions from the transport sector on the territory of the Republic of Croatia amounted to 36.6% of total CO_2 emissions in 2019 [38]. The largest share, 96.4%, is still accounted for by road transport, followed by maritime and river transport with 2.4% [38]. The following formula is used to calculate the reduction in CO_2 emissions by reducing energy consumption [39]:

$$E = \left(\frac{F \cdot \delta}{1000}\right)\sigma \cdot \phi \quad (2)$$

where ***E*** is the emission of CO_2 measured in tons; ***F*** is diesel consumption in litters; $\boldsymbol{\delta}$ is diesel density (equal to 0.845) [40]; $\boldsymbol{\sigma}$ is a factor of calorific value (GJ of energy obtained per ton of diesel) which is equal to 4.71 GJ/t [38]; and $\boldsymbol{\phi}$ is emission factor (ratio of tons of CO_2 per each GJ of energy obtained by burning diesel fuel), which is equal to 74.1 for diesel [38].

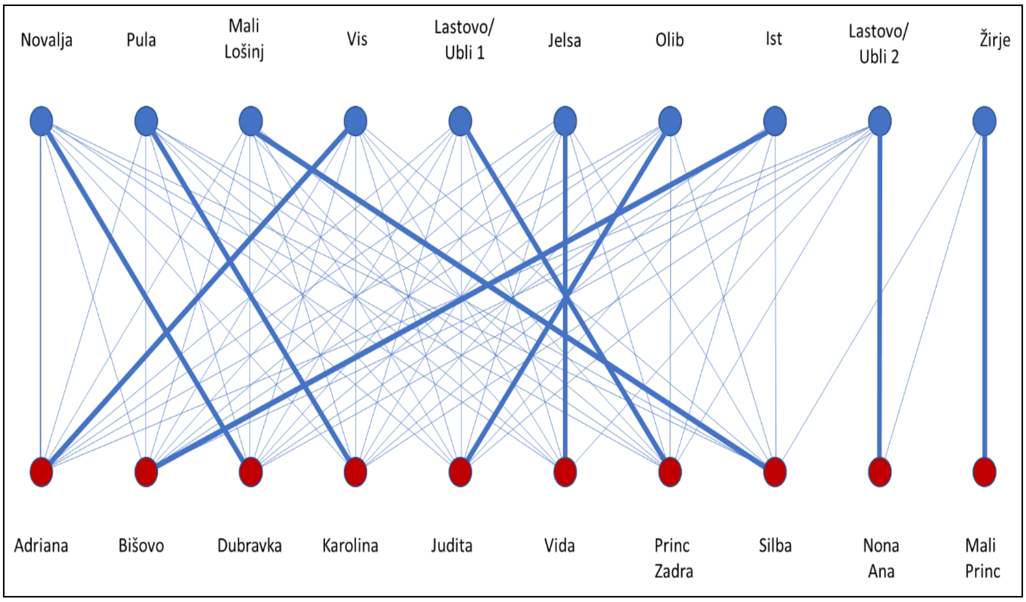

Figure 2. Connecting high-speed boats and speed boat lines from the aspect of propulsion energy consumption—out of season.

Applying this methodology to all three seasons, we can quantify potential savings and environmental benefits as demonstrated by the following Table 3.

Table 3. Amount of CO_2 Emissions—Initial and Optimal Assignment.

	Initial Assignment Weekly Fuel Consumption (in l)	**Optimal Assignment Weekly Fuel Consumption (in l)**
out of season	141,170.94	139,376.94
low season	156,909.64	155,535.42
high season	172,803.64	170,976.28
Annual fuel consumption (in l)	8,573,942.92	8,482,845.62
Annual amount of CO_2 emissions (in t)	22,926.72	22,683.13

Source: Authors.

Table 3 shows that the optimal arrangement of the boats saves 91,097.30 L of fuel or EUR 69,233.95 and reduces CO_2 emissions by 243.59 tons. This confirms that the optimal arrangement of the boats also reduces the emission of CO_2 and other greenhouse gasses due to the lower consumption of propulsion energy. A total of 9,744 trees are needed to compensate for 243.59 tons of CO_2 emissions, as one tree absorbs an average of 25 kg of CO_2 per year [41]. It should be noted that the calculation is based on a relatively small sample and that these figures would be significantly higher if more boat lines and more boats were taken into account.

6. Comparison of Edmonds' Algorithm with Mixed-Integer Programming

To our knowledge, assignments of boats have not been analyzed by Edmonds' algorithm, but by mixed-integer programming. Perfect matching can indeed be solved by using mixed-integer programming. Let $G(V, E, \phi)$ be any graph with vertex set V, an edge set E and a weighting function $\phi : E(G) \to \mathbb{R}$. Optimal perfect matching (of minimal weight) can be found using mixed-integer programming where there is one binary variable b_e for each edge $e \in E(G)$; the goal function is:

$$\sum_{e \in E} b_e \cdot \phi(e) \tag{3}$$

and there is a constraint for each vertex $v \in V(G)$ given by:

$$\sum_{\substack{e \in E \\ e \text{ is incident to } v}} b_e = 1 \tag{4}$$

However, this algorithm is non-polynomial. Considering that the number of edges in our problems increases proportionally with the squared number of boats, the solution for a large number of boats might become intractable while Edmonds' algorithm will solve it almost instantly.

Both methods are not heuristics, but provide exact optimal solutions. Hence, the key advantage of our approach is its scalability to much larger problems.

7. Conclusions

The concept of optimization in maritime transport is most strongly represented in research on liner shipping and on transport and logistics processes in shipping. In the context of maritime passenger traffic, there are still research gaps and a lack of literature regarding the optimization of maritime passenger traffic.

The main objective is to achieve a more efficient system of maritime passenger traffic that ensures its long-term sustainability by reducing the consumption of propulsion energy, costs and the emission of harmful gasses into the atmosphere. The authors presented an efficient algorithm for the reduction in propulsion energy consumption in coastal maritime passenger lines systems by reassigning boats to the lines that they service. Problem was modeled by bipartite graph and the solution was obtained by searching for optimal matching using Edmonds' algorithm. This algorithm found a much more efficient assignment that could result in a significant reduction in propulsion energy consumption, thus providing substantial savings and ecological benefits.

This research has some limitations. Note that the suitability of boats for lines is expressed as a 0/1 matrix. Hence, some finer nuances of the suitability of ships are not taken into consideration (such as: more comfortable boats might be better for the lines with the most passengers although other ones might satisfy minimal criteria). Addressing such issues is expected in subsequent research. Further, it is assumed here that no unpredicted events take place (bad weather or boat malfunctions). Analyzing such uncertainties using the methodology presented in this paper might be a very challenging task. A completely different approach is successfully used in papers [20,42].

The model was tested on the example of the Republic of Croatia, which is a very representative example due to its coastal indentation, the large number of inhabited islands and the established transportation system between the islands and the mainland and between the islands themselves. In this case, the optimal arrangement of boats saves 91,097.30 L of fuel yearly or EUR 69,233.95 and reduces CO2 emissions by 243.59 tons. A total of 9744 trees are needed to compensate for 243.59 tons of CO_2 emissions. The calculation is based on a relatively small sample and savings would be significantly higher if more boat lines and more boats were taken into account.

The proposed model leads to a lower consumption of propulsion energy, which is good from an environmental and financial point of view. These measures enable financial savings for further investments into the system, meet the institutional regulations and requirements and all stakeholders of the system, but also create conditions for the long-term sustainable development of the coastal maritime passenger lines system as well as the conditions for further research that would significantly help the public and private sectors. A recommendation for future research is supplementing the model with other parameters such as greater benefits for passengers.

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References

1. Mišura, A. Contribution to Optimization of the Coastal Liner Maritime Passenger Transport System. Ph.D. Thesis, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia, 2023. Available online: https://urn.nsk.hr/urn:nbn:hr:187:637481 (accessed on 30 September 2024).
2. Xia, Z.; Guo, Z.; Wang, W.; Jiang, Y. Joint optimization of ship scheduling and speed reduction: A new strategy considering high transport efficiency and low carbon of ships in port. *Ocean Eng.* **2021**, *233*, 109224. [CrossRef]
3. Li, S.; Jia, S. The seaport traffic scheduling problem: Formulations and a column-row generation algorithm. *Transp. Res. Part B Methodol.* **2019**, *128*, 158–184. [CrossRef]
4. Pasha, J.; Dulebenets, M.A.; Kavoosi, M.; Abioye, O.F.; Theophilus, O.; Wang, H.; Kampmann, R.; Weihong, G. Holistic tactical-level planning in liner shipping: An exact optimization approach. *J. Shipp. Trade* **2020**, *5*, 8. [CrossRef]
5. Riđanović, J.; Bićanić, Z. The Croatian part of the Adriatic sea in the light of new territorial structure of Croatia. *Acta Geogr. Croat.* **1993**, *28*, 85–96. Available online: https://hrcak.srce.hr/84421 (accessed on 20 July 2024).
6. Lajić, I.; Mišetić, R. Demographic Changes on Croatian Islands at the Beginning of the 21st Century. *Migr. I Etničke Teme* **2013**, *29*, 169–199. [CrossRef]
7. Gračan, D.; Jugović, A.; Aksentijević, D.; Gračan, L.; Barkiđija Sotošek, M. Analysis and trends of maritime passenger traffic in European Union. In Proceedings of the Economic and Social Development 88th International Scientific Conference on Economic and Social Development—Roadmap to NetZero Economies and Businesses, Book of Proceedings, Dubai, UAE, 19–20 October 2022; pp. 200–213.
8. Mišura, A.; Sopta, D.; Perić-Hadžić, A. Impact of Traffic Connectivity on Island Development. *Naše More* **2020**, *67*, 69–77. [CrossRef]
9. Iksan, N.; Tufail, A.; Apong, R.A.; Hidayatullah, A.F. Optimizing Maritime Passenger Transfer in Rich Vehicle Routing Problem Using a Hybrid Genetic Algorithm. *IEEE Access* **2024**, *12*, 80153–80164. [CrossRef]
10. Barone, G.; Buonomano, A.; Forzano, C.; Palombo, A. Implementing the dynamic simulation approach for the design and optimization of ships energy systems: Methodology and applicability to modern cruise ships. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111488. [CrossRef]
11. Mulder, J.; Dekker, R. *Optimization in Container Liner Shipping*; Econometric Institute Report, Erasmus School of Economics: Rotterdam, The Netherlands, 2016; pp. 1–24. Available online: https://hdl.handle.net/1765/79911 (accessed on 5 June 2024).
12. Tran, N.K.; Haasis, H.-D. Literature survey of network optimization in container liner shipping. *Flex. Serv. Manuf. J.* **2013**, *27*, 139–179. [CrossRef]
13. El Noshokaty, S. Shipping optimization systems (SOS) for tramp: Stochastic cargo soft time windows. *J. Shipp. Trade* **2021**, *6*, 1–19. [CrossRef]
14. Martínez-López, A.; Chica-González, M. Joint Optimization of Routes and Container Fleets to Design Sustainable Intermodal Chains in Chile. *Sustainability* **2021**, *12*, 2221. [CrossRef]

15. Fan, H.; Yu, J.; Liu, X. Tramp Ship Routing and Scheduling with Speed Optimization Considering Carbon Emissions. *Sustainability* **2019**, *11*, 6367. [CrossRef]
16. Giavarina dos Santos, P.T.; Borenstein, D. Multi-objective optimization of the maritime cargo routing and scheduling problem. *Int. Trans. Oper. Res.* **2022**, *31*, 221–245. [CrossRef]
17. Buonomano, A.; Del Papa, G.; Giuzio, G.F.; Maka, R.; Palombo, A. Advancing sustainability in the maritime sector: Energy design and optimization of large ships through information modelling and dynamic simulation. *Appl. Therm. Eng.* **2023**, *235*, 121359. [CrossRef]
18. Wang, S.; Meng, Q. Sailing speed optimization for container ships in a liner shipping network. *Transp. Res. Part E* **2012**, *48*, 701–714. [CrossRef]
19. Wang, S.; Meng, Q.; Liu, Z. Bunker consumption optimization methods in shipping: A critical review and extensions. *Transp. Res. Part E* **2013**, *53*, 49–62. [CrossRef]
20. Santos, A.M.P.; Fagerholt, K.; Guedes Soares, C. A stochastic optimization algorithm for the supply vessel planning problem under uncertain demand and uncertain weather conditions. *Ocean Eng.* **2023**, *278*, 114428. [CrossRef]
21. Violić, A.; Debelić, B. The Role of the Maritime and Traffic Policies as a Function of Sustainable Development of Traffic and Shipping Industry. *Pomor. Zb.* **2013**, *47–48*, 13–26. Available online: https://hrcak.srce.hr/120243 (accessed on 21 August 2024).
22. Wang, K.; Yan, X.; Yuan, Y.; Jiang, X.; Lin, X.; Negenborn, R. Dynamic optimization of ship energy efficiency considering timevarying environmental factors. *Transp. Res. Part D* **2018**, *62*, 685–698. [CrossRef]
23. Czermanski, E.; Pawłowska, B.; Oniszczuk-Jastrząbek, A.; Cirella, G. Decarbonization of Maritime Transport: Analysis of External Costs. *Frointers Energy Res.* **2020**, *8*, 28. [CrossRef]
24. European Maritime Transport Environmental Report 2021. European Environment Agency. Available online: https://www.eea.europa.eu/publications/maritime-transport/ (accessed on 30 September 2024).
25. Radonja, R.; Jugović, A. Shipowners' business policy in the context of development in the environmental legislatio. *Pomorstvo* **2011**, *25*, 319–341. Available online: https://hrcak.srce.hr/75332 (accessed on 21 August 2024).
26. Hiranandani, V. Sustainable development in seaports: A multi-case study. *WMU J. Marit. Aff.* **2014**, *13*, 127–172. [CrossRef]
27. Blagojević, B.; Bašić, J. Concept Design of a Fast Craft with Hybrid Propulsion. *Naše More* **2013**, *60*, 91–96.
28. Wang, K.; Yan, X.; Yuan, Y.; Li, F. Real-time optimization of ship energy efficiency based on the prediction technology of working condition. *Transp. Res. Part D* **2016**, *46*, 81–93. [CrossRef]
29. Edmonds, J. Maximum matching and a polyhedron with 0,1-vertices. *J. Res. Natl. Bur. Stand. Sect. B* **1965**, *69*, 125–130. [CrossRef]
30. Gabow, H.N. An Efficient Implementation of Edmonds' Algorithm for Maximum Matching on Graphs. *J. ACM* **1976**, *23*, 221–234. [CrossRef]
31. Edmonds, J. Paths, trees, and flowers. *Can. J. Math.* **1965**, *17*, 449–467. [CrossRef]
32. Buble, M. *Menadžerske vještine*; Sinergija: Zagreb, Croatia, 2006; pp. 37–38.
33. Dumas, J.; Sorce, J.; Virzi, R. Expert Reviews: How many experts is enough? In Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting, San Diego, CA, USA, 9–13 October 1995; pp. 228–232. [CrossRef]
34. Yao, B.; Yu, B.; Chen, G.; Mu, R.; Zong, F. Application of Discrete Mathematics in Urban Transportation System Analysis. *Math. Probl. Eng.* **2014**, *2014*, 212356. [CrossRef]
35. Matoušek, J.; Gartner, B. *Understanding and Using Linear Programming*; Springer: Berlin, Germany, 2007; pp. 31, 12.
36. Coastal Liner Services Agency. Available online: https://agencija-zolpp.hr/ (accessed on 21 August 2024).
37. Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the Monitoring, Reporting and Verification of Carbon Dioxide Emissions from Maritime Transport, and Amending Directive 2009/16/EC. Available online: https://eur-lex.europa.eu/eli/reg/2015/757/oj (accessed on 12 July 2024).
38. Croatian Greenhouse Gas Inventory for the Period 1990–2019 (National Inventory Report 2021).; Submission under the United Nations Framework Convention on Climate Change and Kyoto Protocol, Ministry of Economy and Sustainable Development. Available online: https://www.haop.hr/sites/default/files/uploads/dokumenti/012_klima/dostava_podataka/Izvjesca/Croatian%20NIR%202021_0.pdf (accessed on 30 September 2024).
39. Franić, Z. Monitoring, reporting and verification of CO_2 emissions in maritime transport. *Sigurnost* **2021**, *63*, 189–201. [CrossRef]
40. Uredba o utvrđivanju najviših maloprodajnih cijena naftnih derivata, Narodne novine 105/2022. Available online: https://narodne-novine.nn.hr/clanci/sluzbeni/2022_09_105_1546.html (accessed on 30 September 2024).
41. Ecotree. Available online: www.ecotree.green (accessed on 30 September 2024).
42. Santos, A.M.P.; Fagerholt, K.; Laporte, G.; Guedes Soares, C. A stochastic optimization approach for the supply vessel planning problem under uncertain demand. *Transp. Res. Part B Methodol.* **2022**, *162*, 209–228. [CrossRef]