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STUDY OF INLAND WATERWAY TRANSPORT ROUTING OPTIONS UNDER CONDITIONS OF UNCERTAINTY IN NAVIGATIONAL RESTRICTIONS

Summary. Given the uncertainty of the navigating conditions on the Danube River, the hydrological situation on the Bulgarian leg of the river is predicted using ARIMA methods. The forecast is based on statistical daily hydrological data for a period of five years. A mathematical routing model is developed under the condition that it is not possible for a self-propelled vessel to continue its voyage due to draft limitation. Options including waiting for navigation opening, partial lightening on a barge, and a complete or partial modal shift to rail or road transport through an alternative port are considered. An acceptable option is determined, taking into account the additional costs and transit time. A routing simulation is made using SPSS software.

1. INTRODUCTION

The advantages of inland waterway transport in terms of its environmental impact, capacity, and efficiency often make it attractive for the main legs of multimodal/intermodal routes. However, at the same time, significant efforts are needed to ensure its good interaction with the remaining modes of transport, taking into account the navigational conditions of the river, which are closely related to the hydrological situation.

Like other modes of transport, inland waterway transport has to deal with natural phenomena affecting navigational conditions and infrastructure [19]. In this regard, many studies have focused on the water level as a major challenge for the development of inland waterway transport [12-14, 24, 25]. In rainy periods, there is a risk of flooding, while in dry periods, the water level is low, and some rivers freeze at certain times of the year [12]. These three natural phenomena (heavy rainfall, drought, and freezing) are serious challenges, making navigation difficult and sometimes impossible. Studies have also shown a clear potential to improve cargo transportation on inland waterways such as the Rhine-Main-Danube corridor, including modeling the effects of navigational conditions [15]. Inland waterway transport is more uncertain than transport by road and rail, but risk is ignored in a number of transport models, while we are witnessing many extreme climate changes affecting shipping conditions.

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Analyses of the influence of the meteorological and hydrological conditions of the Danube River have been considered by a number of authors in different periods [4-9, 26]. Authors have noted that the hydrological regime of the Danube River is characterized by spring high water and summer-autumn low water stands. Maximum fairway depth values are monitored in April and May. Autumn high water stands are observed in October and November, and low water stands are observed in August and September.

The increasing variability in the hydrologic cycle (and, therefore, water levels) that can be expected under climate change scenarios suggests that the frequency and magnitude of navigational hindrances associated with low water levels may increase in the future. However, there are adaptation options that can limit the impact of low water levels on navigation. Such options include fleet management in favor of smaller vessels (less affected by low water levels due to their shallow draft), improvements in vessel shape and materials, and more intensive hydro-engineering works to maintain and manage the waterway (the latter with a clear potential impact on the hydromorphology of the river) [21]. During periods of low water, the cargo-carrying capacity of inland vessels is reduced, and therefore, the transport supply is limited while the transport demand remains the same. This affects the security of the supply chain [27]. The impact of periods of low water on inland navigation has been considered by a number of authors [2, 3, 10, 11, 17, 20, 23]. Research in [16, 18] quantified the impact of periods of low water on inland shipping freight rates for the Rhine and the potential impacts of climate change on the shares of different transport modes.

This paper assesses the potential effects of low water levels on Rhine and Danube navigation in the context of weather variability and a range of climate change scenarios. In [11], a long-term analysis of multimodal transport for the period 2005–2050 was presented, and the impact of changes in water depth conditions on transport costs and the modal shift among three competing modes of transport (by inland waterways, road, and rail) were analyzed. In [1], calculations can be found on measures to adapt to inland shipping (e.g., new types of vessels or infrastructural changes). At low water levels, it is necessary to look for a rational way to deliver goods, including the parallel or alternative involvement of rail and road transport.

2. METHODS

2.1. Average weekly levels of the Danube River at the port of Ruse, Bulgaria

The data for the model used in the present study are the average weekly levels of the Danube at the port of Ruse for the period from 2017-2022. Four ARIMA models are used to forecast the average local level for the first week after the period included in the model. Table 1 summarizes the most important results.

Table 1

Summary of the considered models

№	Model/ Characteristics and forecast	Determination factor	Normalized BIC factor	Forecast level [cm]
1	ARIMA (0,1,2)	0,852	8,321	360,25
2	ARIMA (1,0,1)	0,856	8,320	342,57
3	ARIMA (2,0,1)	0,856	8,340	347,47
4	ARIMA (1,0,2)	0,857	8,339	346,14

Table 1 shows that the models have very similar values of the normalized Bayesian information criterion (BIC) and determination factors. It would be difficult to favor one model over others, as there is no model for which the determination is significantly better than the others. However, the normalized BIC is significantly less complex than the other models. For that reason, any model can be selected for forecast purposes [22]. One approach to making a final estimate is to follow Laplace’s principle: when there is no reason (and/or additional information) to believe that a certain situation is more likely than another in a set of situations, it should be assumed that all situations are equally likely to occur. Following this principle, it should be assumed that all four models are equally likely (with equal weight), and as a final forecast, the average of the forecast levels from these models should be 349.11 cm. Likewise, a forecast can be made for any point of interest on the river.

2.2. Feasible solutions using rail and/or road transport or a barge when the river vessel cannot continue its voyage with all its cargo

Depending on the minimum fairway depth along the inland waterway route, several scenarios are possible.

Scenario 1

The minimum fairway depth allows for the unhindered transportation of goods by a river vessel from the port of departure A to the port of destination B. In this scenario, no additional transport expenses arise.

Scenario 2

A hindrance to navigation has arisen at an intermediate point C, where the minimum fairway depth restricts smooth transportation from the port of departure A to the port of destination B.

Scenario 2.1

If the minimum fairway depth is below the vessel's empty draft, the vessel cannot continue its voyage along the route even if it is fully discharged at the nearest intermediate port before the hindrance point C. In this case, the only option (excluding air transport, which is practically unfeasible due to the nature of the goods shipped by inland waterway transport) is the modal shift to rail and/or road transport via the transshipment of the whole lot.

Scenario 2.2

The minimum fairway depth at the hindrance point is in the range between the vessel's empty draft and the vessel's draft fully laden (with all cargo on board). In order to continue, the vessel has to be lightened by a certain amount of cargo. This can be carried out in a barge, or the cargo can be partially shifted to rail and/or road transport. In Scenarios 2.1 and 2.2, additional costs are incurred (e.g., the cost of chartering a barge or freight for rail wagons and/or trucks, penalties per day for delayed cargo delivery, and additional costs for transshipment operations).

A rational solution is sought in the event that the vessel cannot continue its voyage with its entire cargo on board, minimizing all additional costs. An optimization mathematical model based on mixed integer linear programming is proposed, which combines the two options by which the vessel cannot continue its voyage with all its cargo on board.

Designations of known parameters are as follows:

m_1 – cargo capacity of a wagon [t];
m_2 – cargo capacity of a truck [t];
c_1 – freight per wagon [EUR];
A_1 – maximum number of wagons available for employment;
A_2 – maximum number of trucks available for employment;
S_1 – river distance between the nearest intermediate port before the hindrance point C and the port of destination B [km];
S_2 – road distance between the nearest intermediate port before the hindrance point C and the port of destination B [km];
R – transshipment rate at the intermediate port before the hindrance point C [t/24 h];
V_1 – speed of the vessel [km/h];
V_2 – speed of the vessel in convoy with a barge [km/h];
H – minimum fairway depth at the hindrance point C (estimated by forecasting) [m];
c_3 – bareboat charter rate of a barge [EUR/24 h];
c – daily penalty for delayed cargo delivery [EUR/24 h];
c_r – transshipment price in the intermediate port before the hindrance point C [EUR/t];
d_1 – draft of the vessel empty;
d_2 – draft of the vessel fully laden;

m – cargo on board the vessel [t]; and

$\widetilde{c_2}$ – freight per ton-kilometer by truck [EUR/tkm].

Parameters that can be calculated from the known ones are as follows:

c_2 – freight for transportation by one truck [EUR] and

M^* – mass of cargo to be transshipped to lighten a vessel [t].

Designations of unknown values, which are to be determined through a mathematical model, are as follows:

x – number of necessary wagons;

y – number of necessary trucks;

$z = \begin{cases} 0 - without\ a\ barge \\ 1 - \quad using\ a\ barge \end{cases}$ – binary variable indicating whether to use a barge or not; and

U – additional costs above the plan [EUR].

Values obtained directly from the input data are as follows:

– freight per truck [EUR],

$$c_2 = \widetilde{c_2} m_2 S_2, \text{ [EUR], and} \tag{1}$$

– function $M^*(H)$, which determines the mass of cargo by which the vessel has to be lightened:

$$M^*(H) = \begin{cases} m, & H \leq d_1 \\ m\frac{H-d_1}{d_1-d_2} + m, & d_1 < H < d_2 \\ 0, & H \geq d_2 \end{cases}, \text{ [t].} \tag{2}$$

Considering the specific problem, the freight per truck is calculated using the freight rate per ton-kilometer, the distance to be driven, and the truck's payload. The freight per wagon is assumed to be fixed based on its full payload. The function that gives the mass of cargo for lightening can be assumed to be piecewise linear. When the minimum fairway depth is below the vessel's empty draft d_1, the entire load m must be transshipped. When the minimum fairway depth is above the vessel's draft when fully laden d_2, the vessel can proceed with its full load (i.e., it does not need to be lightened. When the fairway depth is between d_1 and d_2, the load for lightening M^* is obtained, assuming it decreases linearly with the increase of the current minimum fairway depth. Fig. 1 represents the function M^* (H), which represents the load for lightening depending on the minimum fairway depth at the hindrance point C.

It is necessary to compute the following to calculate the additional costs:

$$\frac{M^*}{R} \text{ – number of days required for transshipment operations;} \tag{3}$$

$$\frac{S_1}{V_1 - V_2} * \frac{1}{24} \text{ – number of days for barge hire;} \tag{4}$$

$$2\frac{M^*}{R} + \frac{S_1}{V_2} * \frac{1}{24} \text{ – number of days for barge hire.} \tag{5}$$

In (3), the number of days is calculated as the ratio of the mass to be lightened to the port transshipment rate per day. Only one additional transshipment is carried out (from the vessel to the barge or to wagons/trucks), as the discharge at the final port of destination is accounted for in the projected costs and does not entail additional expenses.

The vessel's speed in a convoy with a barge must be considered to calculate the additional number of days for barge hire (3). This speed is always lower than the speed of the vessel proceeding alone. As a result, there is an additional delay caused by the difference in the assumed speed of the vessel V_1 and the convoy speed of a barge V_2. This additional delay is the ratio of the river distance S_1 to the difference in speed (the division by 24 is due to the fact that the delay is measured in days and speed is measured in km/h). The number of days of barge hire is the sum of the time for transshipment at the intermediate port, the time for discharge at the port of destination, and the transit time. Assuming that the discharge rate of the port of destination is equal to the transshipment rate at the intermediate port, we obtain (5).

The fact that there is no additional delay by rail and/or road transport should also be considered, as the speed of trucks and trains significantly exceeds the speed of vessels, while the river and land distance between the two ports is comparable. Thus, the projected transit time by river from the intermediate port to the port of destination is significantly longer than the transit time by rail or road transport. Only the delay due to transshipment operations to lighten the vessel should be considered.

Another peculiarity that arises when formulating the mathematical model is that if a barge is chartered, it can accommodate the entire cargo necessary for lightening M^*. In this case is no need to involve road or rail transport. Similarly, if rail and/or road transport is used, then is no need to charter a barge (i.e., chartering a barge and using rail and/or road transport are assumed to be incompatible).

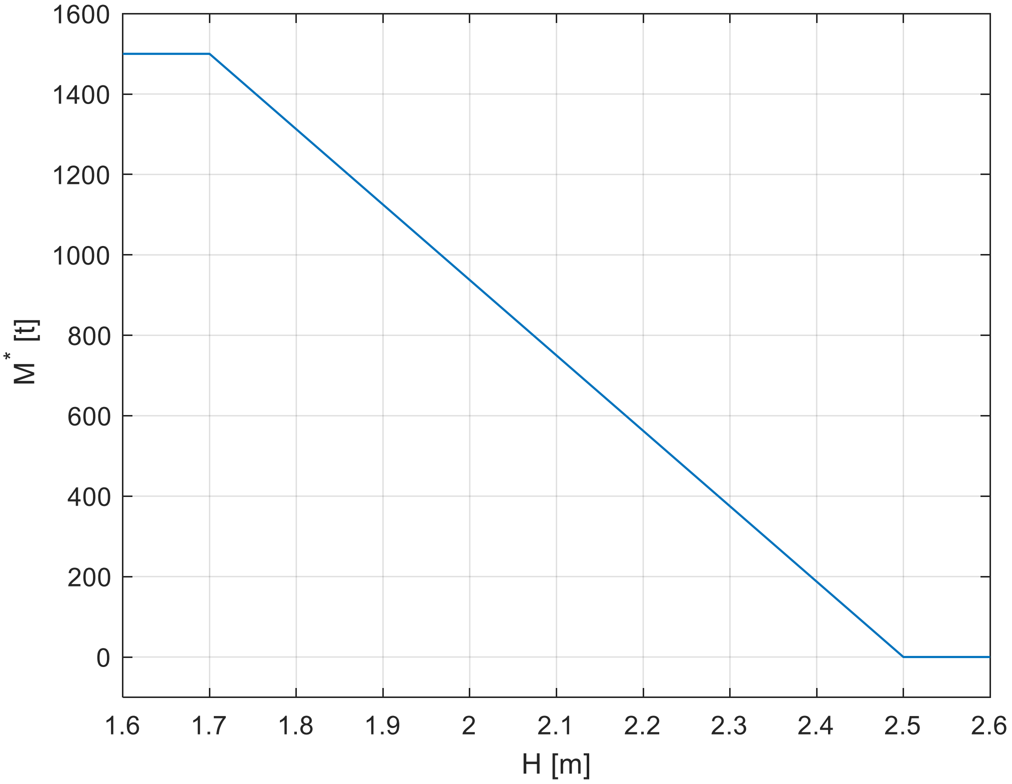

Fig. 1. Load lightening depending on the minimum fairway depth at the hindrance point C

Considering the mentioned specifics, the following expenses can be formulated:

c_1x – freight for rail transport [EUR]; (6)

c_2y – freight for road transport [EUR]; (7)

$c_3(2\frac{M^*}{R}+\frac{S_1}{V_2}\frac{1}{24})z$ – barge hire [EUR]; (8)

$c_r\frac{M^*}{R}$ – transshipment charges [EUR]; (9)

$c(\frac{M^*}{R}+\frac{S_1}{V_1-V_2}\frac{1}{24})z$ – penalty for delayed delivery due to the barge charter [EUR]; and (10)

$c\frac{M^*}{R}$ – penalty for delayed delivery due to transshipment operations, [EUR]. (11)

Costs (6) and (7) are related to the use of rail wagons and trucks (number of wagons/trucks at their freight rate). Meanwhile, (8) is associated with the barge charter. The two loading/unloading times at the intermediate and destination ports, presented in brackets (8), and the transit time of the barge in convoy with the vessel are given. In (9), constant costs for the transshipment of the necessary cargo for lightening are given, regardless of the mode of its further transportation. The penalties in (10) are related to the transshipment time at the intermediate port and the additional transit time of the barge in convoy with the vessel. If we denote the additional costs when a barge is chartered as U_1 and the costs when rail and/or road transport is used as U_2, then

$$U_1 = [c_3\left(2\frac{M^*}{R}+\frac{S_1}{V_2}\frac{1}{24}\right)+c\left(\frac{M^*}{R}+\frac{S_1}{V_1-V_2}\frac{1}{24}\right)+c_r\frac{M^*}{R}]z \text{ [EUR]} \quad (12)$$

and

$$U_2 = c_1 x + c_2 y + \left(c\frac{M^*}{R} + c_r\frac{M^*}{R}\right)(1 - z)\ [\text{EUR}]. \tag{13}$$

The costs for a barge (12) consist of hire costs, the penalty due to the additional delay, and the costs associated with transshipment operations. These costs become relevant only if $z = 1$ (i.e., transshipment is performed on a barge), and they are inactive if $z = 0$ (i.e., transshipment is on trucks and/or wagons only. In (13), at $z = 0$ (i.e., when transportation is done by rail wagons and/or trucks), the costs (13) become active. In (13), $c_r\frac{M^*}{R}$ represents the cost of transshipment operations. Meanwhile, for c $\frac{M^*}{R}$, the mass for transshipment M^* is between 0 and m. When M^* takes a value between 0 and m without being equal to either of them (i.e., $M^* \neq 0$ and $M^* \neq m$), then the penalty cost in (13) depends on only the additional delay of the vessel $c\frac{M^*}{R}$.

When $M^* = 0$, there is no cargo for transshipment and the vessel continues its voyage without incurring additional costs. If $M^* = m$, then $c\frac{M^*}{R}$ in (13) should be nullified, as all cargo is transshipped to rail and/or road transport only because the vessel cannot continue its voyage, and (12) should be nullified because the barge option is not feasible. When M^* takes a value between 0 and m without being equal to either of them (i.e., $M^* \neq 0$ and $M^* \neq m$), then in (13), the number of wagons x and the number of trucks y should be 0 if the barge option is chosen ($z = 1$). Since the value of M^* is directly dependent on the value of the minimum fairway depth H, three scenarios can be considered:

Scenario 1: $H \geq d_2$ (i.e., $M^* = 0$)

In this scenario, no cargo is transshipped (i.e., the vessel continues its voyage with no additional costs).

Scenario 2: $H < d_1$ (i.e., $M^* = m$)

In this scenario, all cargo needs to be transshipped. Additional costs will accumulate, and there is no barge alternative. The additional costs should be minimized. The objective function is

$$min\, U = minU_2 = c_1 x + c_2 y + c_r\frac{M^*}{R}\ [\text{EUR}]. \tag{14}$$

Scenario 3: $d_1 < H < d_2$ (i.e., $0 < M^* < m$)

In this scenario, part of the cargo needs to be transshipped. As a result, additional costs will accumulate, and these additional costs should be minimized. The objective function is

$$min\, U = \min\,(U_1 + U_2) = \left[c_3\left(2\frac{M^*}{R} + \frac{S_1}{V_2}\frac{1}{24}\right) + c\left(\frac{M^*}{R} + \frac{S_1}{V_1 - V_2}\frac{1}{24}\right) + c_r\frac{M^*}{R}\right]z + c_1 x + c_2 y + \left(c\frac{M^*}{R} + c_r\frac{M^*}{R}\right)(1 - z)\ [\text{EUR}]. \tag{15}$$

Finally, the mathematical optimization models for the individual scenarios are as follows:

Scenario 1: a mathematical model is not needed, as the vessel continues its voyage without additional costs.

Scenario 2: the vessel cannot continue even with an empty draft, so all cargo m is transshipped to rail wagons and/or trucks.

$$min\, U = minU_2 = c_1 x + c_2 y + c_r\frac{m}{R}\ [\text{EUR}], \tag{16}$$

$$m_1 x + m_2 y \geq m\ [\text{t}] \tag{17}$$

$$x \leq A_1 \tag{18}$$

$$y \leq A_2 \tag{19}$$

$$x \geq 0 \tag{20}$$

$$y \geq 0 \tag{21}$$

$$x, y \in \mathbb{Z}. \tag{22}$$

Models (16)-(22) represent a standard integer linear optimization task. The objective function (16) is the cost of rail wagons, trucks, and transshipment. Constraint (17) is imposed to transship the entire cargo to rail wagons or trucks. Constraints (18) and (19) indicate the maximum number of available rail wagons and trucks. Conditions (20) and (21) correspond to the fact that the number of wagons and trucks cannot be negative. Constraint (22) imposes the integrality of the unknowns.

Scenario 3: Some of the cargo needs to be transshipped, and the rest will continue with the vessel. This scenario is more peculiar than the others because if a barge is chartered, rail wagons and/or trucks should not be employed. Similarly, if rail wagons and/or trucks are used, a barge should not be chartered. Such constraints lead to a non-convex feasible region. Such a problem was overcome by introducing a binary unknown variable *z* earlier, which takes a value of 1 if it is more appropriate to charter a barge and otherwise takes a value of 0.

$$min\,U = \min\,(U_1 + U_2) = \left[c_3\left(2\frac{M^*}{R} + \frac{S_1}{V_2}\frac{1}{24}\right) + c\left(\frac{M^*}{R} + \frac{S_1}{V_1 - V_2}\frac{1}{24}\right) + c_r\frac{M^*}{R}\right]z +$$

$$c_1x + c_2y + \left(c\frac{M^*}{R} + c_r\frac{M^*}{R}\right)(1 - z)\ [\mathrm{EUR}], \tag{23}$$

$$x + y \leq W(1 - z) \tag{24}$$

$$m_1x + m_2y \geq M^* - Wz\ [\mathrm{t}] \tag{25}$$

$$x \leq A_1 \tag{26}$$

$$y \leq A_2 \tag{27}$$

$$x \geq 0 \tag{28}$$

$$y \geq 0 \tag{29}$$

$$x, y\ \in \mathbb{Z} \tag{30}$$

$$z\ \in \{0,1\} \tag{31}$$

$$W \gg 1. \tag{32}$$

In Models (23)-(32), an unknown, apart from the number of wagons and trucks, is the value of the variable z. The objective function (23) describes the costs and has already been considered. Constraints (26)-(30) have the same meaning as those considered in Scenario 2. In Models (23)-(32), W is a very large arbitrary positive number, exceeding the orders of all parameters in the task. This is reflected in Condition (32). Condition (31) indicates the binary nature of the variable z.

If the use of a barge ($z = 1$) is allowed, then Constraint (24) becomes active; Constraints (24), (28), and (29) require the number of wagons and trucks to be 0; and Constraint (25) will always be satisfied (i.e., it is redundant). In the Objective Function (23), U_2 is canceled and the costs U_1 related only to the barge remain.

If $z = 0$ is allowed (i.e., transport is done without a barge), but only by rail and/or road, then Constraint (24) is always satisfied (i.e., it is redundant), Constraint (25) becomes active and the cargo M^* will be transshipped onto wagons and/or trucks. In the Objective Function (23), U_1 is canceled and the costs U_2 related to transport by rail wagons and trucks remain. In the programming environment Matlab R2021, a program has been developed to solve the posed problem.

3. RESULTS

Numerical examples:

Assuming that most barges used on the Danube have empty drafts between 0.40 and 0.70 m and vessels between 1.20 and 1.70 m, let the following known values of the parameters be given:

$$m = 1500;\ [t]; d_1 = 1.7\ [m]; d_2 = 2.5\ [m];\ m_1 = 50\ [t];\ m_22 = 25\ [t];$$

$$c_1 = 868\ [EUR];\ \tilde{c_2} = 0.15\ \left[\frac{EUR}{tkm}\right];\ S_2 = 216\ [km];\ R = 500\ \left[\frac{t}{24h}\right];$$

$$v_1 = 10\ \left[\frac{km}{h}\right];\ v_2 = 6\ \left[\frac{km}{h}\right];\ A_1 = 25;\ A_2 = 50;\ S_1 = 248\ [km];$$

and

$$c_3 = 1000\ [EUR];\ c_r = 500\ [EUR] c = 400\ [EUR].$$

Example 1: With the given parameters, a minimum fairway depth of $H = 2.65$ m is forecast. In this case, $H > d_2$ and the vessel can continue without transshipment with no additional costs.

Example 2: With the given parameters, a minimum fairway depth of $H = 1.6$ m is forecast. In this case, $H < d_1$, the vessel cannot continue, and all the cargo has to be transshipped onto rail wagons and/or trucks. After applying and solving Models (16)-(22), it is found that the number of rail wagons employed should be 25, and the number of trucks employed should be 10. The total additional cost will be EUR 31,300.

Example 3: With the given parameters, a minimum fairway depth of $H = 2.1$ m is forecast. In this case, $d_1 < H < d_2$, and the vessel can continue partially lightened. The transshipped cargo is $M^* = 750$ t. After applying and solving Models (23)-(32), it is found that the cargo $M^* = 750$ t will be transshipped on a barge and that rail wagons/trucks should not be emloyed. The total additional cost will be EUR 7,106.

Example 4: With the given parameters, a minimum fairway depth of $H = 2.36$ m is forecast. In this case, $d_1 < H < d_2$, and the vessel can continue after partial lightening. This part of the cargo, that will be transshipped, is $M^* = 262.5$ t. After applying and solving Models (23)-(32), it is found that the cargo $M^* = 262.5$ t will be transshipped on a barge and that rail wagons and trucks should not be employed. The total additional cost will be EUR 4,278.

Example 5: With the given parameters, a minimum fairway depth of $H = 2.41$ m is forecast. In this case, $d_1 < H < d_2$, and the vessel can continue after partial lightening. This part of the cargo is $M^* = 168.75$ t. After applying and solving Models (23)-(32), it is found that the cargo $M^* = 168.75$ t will be transshipped onto three rail wagons and one truck, while a barge should not be employed. The total additional cost will be EUR 3,718.

Example 6: With the given parameters, a minimum fairway depth of $H = 2.45$ m is forecast. In this case, $d_1 < H < d_2$, and the ship can continue partially lightened. This part of the cargo is $M^* = 93.75$ t. After applying and solving Models (23)-(32), it is found that $M^* = 93.75$ t of the cargo will be transshipped onto two rail wagons, while no barge or trucks should be employed. The total additional cost will be EUR 1,905. It would be of interest to trace the changes in the additional costs as a function of the minimum fairway depth given certain parameters.

Fig. 2 is a graph showing the change in the additional costs depending on the minimum fairway depth. From the figure, it is clear that the additional costs are the highest below a minimum fairway depth of 1.7 m, which can be explained by the fact that the entire load is transported by rail and/or road transport only. In the range of 1.7 m to 2.4 m, the additional costs decrease linearly. Between these two levels of minimum fairway depth, it is profitable to charter a barge. Just above 2.4 m to 2.5 m, the additional costs start to decrease stepwise, which can be explained by the fact that it is not profitable to charter a barge and that it is more beneficial to use a combination of rail and road transport. At minimum fairway depths above 2.5 m, there are no additional costs, as the vessel can continue its voyage without the need to be lightened. Similarly, the changes in the additional costs with changes in the minimum fairway depth can be traced by setting different values of the parameters (e.g., the penalty for delivery delay or the cost of transshipment operations).

4. CONCLUSION

The mathematical model developed in this study presents a novel approach for navigating the complexities of transport logistics in scenarios where a self-propelled vessel is unable to continue its voyage due to low fairway depth. The model's utility is manifested in its capacity to evaluate various alternative transport routes and determine the most effective solution based on minimizing additional costs and transit time.

Flexibility and risk mitigation: The model considers a range of alternative transport routing options, including delaying the vessel's movement, transferring part of the load to an additional barge, or shifting fully or partly to rail and/or road transport. This versatility allows for significant risk mitigation in delivering cargo to its destination, particularly under challenging water-level conditions.

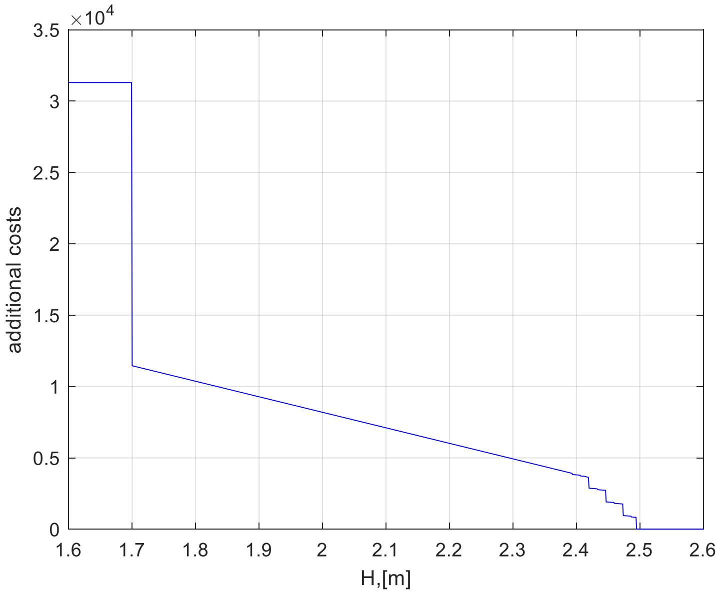

Fig. 2. Additional costs depending on the minimum fairway depth

Cost and time analysis: The model's ability to map incremental costs as a function of minimum fairway depth makes it an important tool for managing logistics costs. This functionality becomes particularly useful in optimizing transport strategies during periods of low river levels.

Simulative capabilities: SPSS software was utilized to simulate transport routes for a comprehensive assessment of transport logistics under varying conditions. This feature adds an essential layer of practicality to the model, enabling it to adapt to different parameters, such as the penalty for delivery delay or the cost of transshipment operations.

Universal applicability: Although the model was developed with a specific focus on the challenges associated with low fairway depths, the utilized approach can be broadly applied to other logistics scenarios. This versatility highlights the value of the model in various transport and logistics planning processes.

Optimal decision-making: Ultimately, the model serves as a powerful decision-making tool, facilitating optimal choices by accurately accounting for the additional costs and transit times associated with different transport routing options.

By considering these fundamental aspects of transport logistics, the mathematical model reveals new opportunities to improve efficiency and reduce costs in the field of inland waterway transport, especially in scenarios impacted by fluctuating fairway depths.

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