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# Real-time monitoring and optimal vessel rescheduling in natural inland waterways

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**Abstract:** Despite the efforts made by the port community and the academia to develop efficient strategies to mitigate the effect of unexpected events on the planning of vessels through natural waterways, most scheduling algorithms developed so far are not against these events unforseen events. These incidents may lead to nonoptimal operation or even to potentially dangerous situations. To tackle this issue, in this paper we propose a real-time monitoring architecture and a series of optimal rescheduling strategies to re-schedule vessels in real time when an unexpected incident is detected. The objective is to reduce the impact of the incident in the overall process while preserving safety. This is done by detecting deviations from the originally scheduled plans and taking the proper measures when incidents are detected, which will depend on the type of anomaly detected. The proposed methodology is applied to the case of the Guadalquivir river, a natural waterway located in the south of Spain.



*Keywords:* Scheduling, Planning, Maritime System, Logistic Systems, Risk-oriented Control.

## 1. INTRODUCTION

Interest in research and innovation in maritime traffic management has been stimulated during last years mainly because of two key factors: the need for improving the efficiency of the overall logistic process to respond to the necessities of an increasingly globalized society (Fratila et al. (2021)) and the raising awareness about the potential negative impact of transportation systems on climate change (Asariotis and Benamara (2012)). This interest has led to the development of novel scheduling and planning algorithms to improve the operation of vessels by reducing transit times and while increasing the levels of security.

In the case of inland ports and transit canals, a significant number of works can be found in the literature trying to solve different problems related to traffic management in waterways such as the Yangtze river (Lalla-Ruiz et al. (2018)) and the Kiel channel (Lübbecke et al. (2019)). Most works focus on minimizing the waterway occupancy and waiting times of all vessels taking into account constraints on the crossings among vessels (Zhang et al. (2019)). There are also several works dealing with channels in which the depth is affected by tides such as Zhang et al. (2020) or Li et al. (2021).

However, most of them provide optimal scheduling plans under ideal operating conditions. This implies, that they may not ensure the optimality and safety of the different operations in the case of unexpected events, such as delays or mechanical failures. More recently, some authors propose to take into account the effect of the uncertainty in the decision making leading to complex optimization problems (Andersen et al. (2021).

Despite these attempts, it is in general a difficult task to formulate a scheduling problem that considers at once all different possible sources of uncertainty that affect navigation in natural waterways. To address this issue, in this work we propose a real-time monitoring approach whereby vessels' trip plans are re-scheduled in case an incident or abnormal behavior is detected. The proposed approach assumes that the position of each vessel in the waterway is constantly emitted using an automatic identification system (AIS)(see Organization (2015)). The AIS information can be employed to detect and classify anomalies in the trajectories of vessels in real time (Rong et al. (2020)). After an anomaly is detected and identified, vessels' trip plans are re-scheduled by means of an optimization problem based on the strategy proposed in Nadales et al. (2022) for scheduling vessels in natural waterways. The rescheduling strategy tries to minimize sailing and waiting times times while mitigating the impact of the detected incident on the original schedule following

The proposed monitoring and rescheduling strategy is simulated and tested for the case of vessels sailing in the Guadalquivir river, a natural waterway connecting the Atlantic ocean and the inland port of Seville, under different scenarios where vessels are affected by arrival delays and speed reductions due to machinery failures.

## 2. PROBLEM STATEMENT

In this work, we consider a set of $N$ vessels that navigate through a bidirectional natural waterway connecting a cargo inland port to the open sea. These vessels can sail upstream or downstream. It is supposed that there are

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**Algorithm 1** Vessels monitoring architecture

```
Schedule trip plans t_i, i = 1,...,N.
Predict expected position z_i(t), i = 1,...,N.
while vessels are navigating do
    if |z_i(t) − z_i^†(t)| ≥ ε_z then
        Generate warning alarm.
        Re-schedule new trip plans t_i , i = 1,...,N.
        Predict new expected trajectory z_i(t), i = 1,...,N.
    end if
end while
```

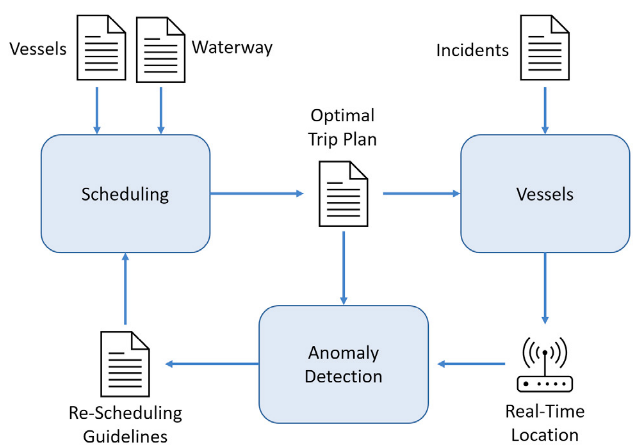


Fig. 1. Monitoring and rescheduling strategy.

expert river pilots who are in charge of adjusting the speed of vessels to meet some optimal trip plan. This plan is a collection of times when each vessel should cross a series of waypoints that divide the waterway into $Z$ different sections. For each vessel $i \in \mathcal{I} = \mathbb{N}_1^N$, this trip plan is denoted as $t_i \in \mathbb{R}^{Z+1} = t_{i,p}\ \forall p \in \mathbb{N}_0^Z$, where $\mathbb{N}$ is the set of natural numbers. Assuming that vessels sail at constant speed in each section, this plan provides the expected trajectory of each vessel, which is denoted as $z_i(t)$.

Due to different unexpected events, vessels can deviate from their originally expected trajectories, thus compromising the optimality and safety of the operation. To tackle this issue, we propose a monitoring system that constantly checks whether or not vessels are following their expected trajectories. This is done by comparing, in real time, the current location of each vessel given by the AIS system, which we denote as $z_i^\dagger(t)$, with its expected location, $z_i(t)$. In case any vessel deviates from its expected trajectory more than a certain threshold, $\epsilon_z$, a warning event is generated, indicating that rescheduling is required to obtain a new trip plan that preserves the safety of the operation. As it will be detailed in Section 5, different rescheduling strategies can be adopted, such as optimizing sailing times or minimizing the impact of the anomaly detected on the rest of the vessels. Once the new optimal trip plan is calculated, this is forwarded to the affected vessels. The proposed monitoring and rescheduling strategy is detailed in Algorithm 1 and represented in Figure 1.

## 3. SCHEDULING PROBLEM

Consider $N$ vessels, $i \in \mathcal{I} = \mathbb{N}_1^{N_u+N_d}$, sailing through a bidirectional natural waterway, where $N_u$ and $N_d$ are the number of vessels sailing upstream and downstream, respectively. The sets of vessels sailing upstream and downstream are denoted as $\mathcal{I}_u$ and $\mathcal{I}_d$, respectively. The waterway in which vessels sail is divided into a total of $Z$ sections. Each of these sections, $p \in \mathbb{N}_1^Z$, is characterized by its length, $d_p$, its minimum width, $w_p$, and the maximum speed at which vessel can sail through it, $\mu_p$. The boundary between sections $p-1$ and section $p$ is denoted as boundary $p$. The extremes of the waterway are given by boundaries 0 and $Z$. Vessels sailing upstream enter the waterway through boundary 0 and exit the waterway through boundary $Z$. Vessels sailing upstream enter the waterway through boundary $Z$ and exit the waterway through boundary 0. Each vessel is characterized by its maximum speed, $v_i$, and its beam, $b_i$. The time when each vessel is expected to be ready to be scheduled is given by $t_i^r$.

The objective is to determine the times $t_{i,p}$ in which the vessels cross each boundary minimizing the time vessels spend waiting and sailing through the waterway while ensuring safety in encountering situations. Both head-on and overtaking encounters are considered according to the international regulation for preventing collisions at sea (Organization (2002).

To solve this problem, we use the following mixed-integer linear programming (MILP) formulation presented in Nadales et al. (2022) in which, besides the crossing times, for each pair of vessels $i, j$ and for each boundary $p$ an additional binary variable $c_{i,j,p}$ is considered:

$$\min_{t,c} J_{sail}$$

$$s.t.$$

$$(t_{i,p} - t_{i,p-1})\min(\mu_p, v_i) \geq d_p, \forall i \in \mathcal{I}_u, p \in \mathbb{N}_1^Z, \quad (1)$$

$$(t_{i,p-1} - t_{i,p})\min(\mu_p, v_i) \geq d_p, \forall i \in \mathcal{I}_d, p \in \mathbb{N}_1^Z, \quad (2)$$

$$t_{i,p} + \Delta_0 \leq t_{j,p} + M \sum_{l \in \mathbb{N}_0^p} c_{i,j,l}, \forall i, j, p, \quad (3)$$

$$t_{j,p} + \Delta_0 \leq t_{i,p} + M\left(1 - \sum_{l \in \mathbb{N}_0^p} c_{i,j,l}\right), \forall i, j, p, \quad (4)$$

$$\sum_{p \in \mathbb{N}_0^Z} c_{i,j,p} \leq 1\ \forall i, j \in \mathcal{I}, \quad (5)$$

$$c_{i,j,p} = 0 \text{ if } b_i + b_j > w_p\ \forall i, j \in \mathcal{I}, \forall p \in \mathbb{N}_1^Z, \quad (6)$$

where the performance index to be minimized, $J_{sail}$, is defined as

$$J_{sail} = \sum_{i \in \mathcal{I}_u} (\alpha_i(t_{i,Z} - t_{i,0}) + \beta_i(t_{i,0} - t_i^r)) + \sum_{i \in \mathcal{I}_d} (\alpha_i(t_{i,0} - t_{i,Z}) + \beta_i(t_{i,Z} - t_i^r)), \quad (7)$$

and $\alpha_i \in \mathbb{R}$ and $\beta_i \in \mathbb{R}$ are weighting factors. Through the employment of this performance index as cost function of the scheduling optimization problem, the objective is to minimize the time vessels are sailing through the waterway and the time vessels are waiting to enter the waterway after they are ready to enter the waterway at time $t_i^r$.

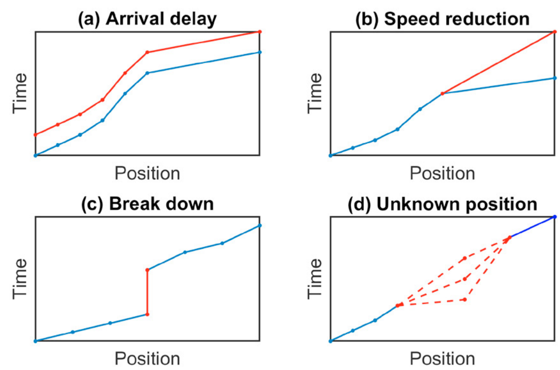


Fig. 2. Types of unexpected events.

Constraints (1) and (2) ensure that vessels never exceed the maximum speed limit of each section. Constraints (3) and (4) guarantee that vessels $i$ and $j$ only encounter in section $p$ if $c_{i,j,p}$ is equal to 1. If the values of these variables for all sections $p$ are equal to zero or if $c_{i,j,0} = 1$, vessels never encounter each other. In addition, the minimum time difference between the encountering of any pair of vessels should be no smaller than $\Delta_0$. Constraint (5) ensures that two vessels only encounter at most once. Constraint (6) ensures that no encountering situations occurs in a section whose width is less that the sum of beams of the two vessels involved (see Nadales et al. (2022) for more details).

This scheduling problem can be employed to obtain the optimal trip plan for a set of vessels assuming that none of them have entered the waterway yet. This problem does not consider vessels already sailing in the waterway, and thus it can not be employed for rescheduling purposes.

*Remark 1.* For simplicity, constraints addressing the issue of tidal wave have not been included in the optimization problems developed in this work. A detailed explanation on how to deal with this issue can be found in Nadales et al. (2022).

## 4. ANOMALIES DETECTION AND IDENTIFICATION

The scheduling problem presented in the previous section provides the optimal times $t^*_{i,p}$ when vessel $i$ should cross the different boundaries $p$. Assuming that vessels sail at constant speed in each section of the waterway, it is possible to obtain the expected location $z_i(t)$ of each vessel. The proposed monitoring system compares in real time this trajectory with the real trajectory given by the locations provided by the AIS system, $z_i^\dagger(t)$. An unexpected incident occurs when the deviation between $z_i(t)$ and $z_i^\dagger(t)$ is greater than a given threshold $\epsilon_z$.

Once an incident is detected, it is classified into one of the four different categories shown in Figure 2. To this end, the average speed of the vessel is estimated from the information provided by the AIS system. To do that, the locations of the vessels in the last $N_w$ are assumed to be known. The four type of accidents considered are:

- *Unknown position.* The AIS signal has not been received for a period of time $\tau^{lost}$.
- *Arrival delay.* Some vessel does not arrive to the waterway at its estimated time of arrival.
- *Break down.* The average speed of some vessel falls below a given threshold.
- *Speed reduction.* The average speed of the vessel is above the break down threshold. In this case, it is assumed that the new speed is the maximum at which the affected vessel can sail.

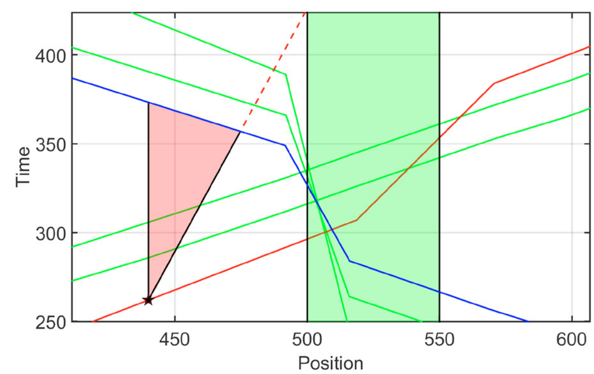


Fig. 3. Illustrative example of feasibility problems due to a speed reduction incident.

## 5. RESCHEDULING STRATEGY

When some incident is detected, the trip plans of vessels are rescheduled. Suppose that an unexpected incident is detected at time $t^\times$ in vessel $i^*$. The location of each vessel $i$ already sailing in the waterway is given by $z_i^\dagger(t^\times)$, its original optimal trip plan is given by $t_i^\dagger$ and the last boundary it crossed before the incident is given by $p_i^\times$. To obtain the new optimal trip plans $t_i$, a new optimization problem must be solved considering the current location of all vessels. To this end, two conflicting issues must be considered. The first one is the performance and safety of the new trip plan. The second one, is the number of vessels affected by the rescheduling. While global solutions that consider all vessels might be more convenient in terms of performance, modifying the original trip plan could have a negative impact on the reputation and competitiveness of the port (Acosta et al. (2007)). Taking this into account, three rescheduling approaches are consider: isolated rescheduling, global rescheduling, and multi-objective rescheduling.

### 5.1 Isolated rescheduling

The objective is to find a new plan for the affected vessel without modifying the trip plans of the rest of vessels. This is achieved by solving the following optimization problem:

$$\begin{aligned}
&\min_{t,c}\ J_{sail} \\
&\quad s.t. \quad (1)-(6) \\
&\quad t_{i,p} = t^\dagger_{i,p}\ \forall i \neq i^*, \forall p \in \mathbb{N}_0^Z, && (8)\\
&\quad t_{i^*,p} = t^\dagger_{i^*,p},\ \forall p < p^\times_{i^*},\ \text{if } i^* \in \mathcal{I}_u, && (9)\\
&\quad t_{i^*,p} = t^\dagger_{i^*,p},\ \forall p \geq p^\times_{i^*},\ \text{if } i^* \in \mathcal{I}_d, && (10)\\
&\quad t_{i^*,p^\times+1} \geq t^\times + \Delta t^\times_{i^*}\ \text{if } i^* \in \mathcal{I}_u, && (11)\\
&\quad t_{i^*,p^\times} \geq t^\times + \Delta t^\times_{i^*}\ \text{if } i^* \in \mathcal{I}_d. && (12)
\end{aligned}$$

Constraint (8) guarantees that the new trip plans of vessels not affected by the incident are equal to the original trip plans. Constraints (9) and (10) guarantee that the crossing times of the boundaries already crossed by vessel $i^*$ are equal to those given by the original trip plans. Constraints (11) and (12) take into account the current position and the distance already sailed by vessel $i^*$, where $\Delta t_{i^*}^{\times}$ is the time needed to sail from the current location of the vessel until the location of the next boundary sailing at maximum speed. Note that, in case of a speed reduction incident, the maximum speed at which vessel $i^*$ can sail, $v_{i^*}$, would be updated to the estimated speed. If a feasible solution exists, this formulation ensures that only the trip plan of the affected vessel is modified.

It may be the case that it is not possible to find a feasible solution without modifying the trip plan of a single vessel. This is illustrated in Figure 3. Suppose that the vessel sailing upstream (coloured in red) suffers an speed reduction incident and that its maximum speed after the incident is given by the slope of the dashed red line. In that case, it can be appreciated how crossing maneuvers with the vessel sailing downstream (coloured in blue) can no longer take place in the safe crossing region (shaded in green) without modifying the trajectory of the vessel sailing downstream.

### *5.2 Global rescheduling*

To solve the problem associated to the isolated rescheduling strategy, we can allow all vessels to modify their trip plans. This is achieved by solving the following optimization problem:

$$\begin{aligned} &\min_{t,c}\ J_{sail} \\ &\quad s.t.\quad (1) - (6) \\ &\quad t_{i,p} = t_{i,p}^{\dagger},\ \forall p < p_i^{\times},\ \text{if } i \in \mathcal{I}_u, && (13)\\ &\quad t_{i,p} = t_{i,p}^{\dagger},\ \forall p \geq p_i^{\times},\ \text{if } i \in \mathcal{I}_d, && (14)\\ &\quad t_{i,p^{\times}+1} \geq t^{\times} + \Delta t_i^{\times}\ \text{if } i \in \mathcal{I}_u, && (15)\\ &\quad t_{i,p^{\times}} \geq t^{\times} + \Delta t_i^{\times}\ \text{if } i \in \mathcal{I}_d. && (16)\end{aligned}$$

Constraints (13) and (14) guarantee that the crossing times of the boundaries already crossed by each vessel $i$ are equal to the original trip plans. Constraints (15) and (16) take into account, for each vessel $i$, the distance travelled following the original plan when the incident is detected, where $\Delta t_i^{\times}$ is the time needed to sail from the current location of the vessel until the location of the next boundary sailing at maximum speed. Note that, in case of a speed reduction incident, the maximum speed at which vessel $i^*$ can sail, $v_{i^*}$, must be updated to the estimated speed.

### *5.3 Multi-objective rescheduling*

To find an optimal solution that ensures feasibility while affecting the least possible number of vessels, a multi-objective approach can be adopted (Deb (2014)). We consider that the trip plan of some vessel $i$ is affected if the arrival time to its final destination deviates from the one given by its previous trip plan. To reduce this deviation a new penalty term is added to the cost function of the global rescheduling problem to penalize the deviation between the arrival time given by the previous trip plan and the arrival time calculated solving the new rescheduling problem. This term is defined as follows:

$$J_{rescheduling} = \sum_{i\in\mathcal{I}_u} |t_{i,Z} - t_{i,Z}^{\dagger}| + \sum_{i\in\mathcal{I}_d} |t_{i,0} - t_{i,0}^{\dagger}| \quad (17)$$

The multi-objective rescheduling problem is formulated following a weighted sum approach in which the cost function is a linear combination of $J_{sail}$ and $J_{rescheduling}$.

$$\begin{aligned}&\min_{t,c}\ J_{sail} + \eta \cdot J_{rescheduling} && (18)\\ &\quad s.t.\quad (1) - (6), (13) - (16)\end{aligned}$$

where $\eta$ is a single weighting parameter that allows the decision maker to obtain different solutions based on which cost is prioritized.

Table 1. Guadalquivir waterway parameters.

| id | $d(km)$ | $\mu(km/h)$ | $w$ | id | $d(km)$ | $\mu(km/h)$ | $w$ |
|---|---|---|---|---|---|---|---|
| **1** | 1.9 | 10.1860 | 1 | **13** | 4.2 | 19.4460 | 8 |
| **2** | 1.4 | 16.6680 | 4 | **14** | 4.5 | 19.4460 | 1 |
| **3** | 4.5 | 16.6680 | 2 | **15** | 3.5 | 22.2240 | 8 |
| **4** | 4.2 | 17.5940 | 4 | **16** | 1.2 | 18.5200 | 4 |
| **5** | 2.0 | 17.5940 | 4 | **17** | 3.4 | 21.2980 | 4 |
| **6** | 5.2 | 18.5200 | 4 | **18** | 1.7 | 23.1500 | 4 |
| **7** | 6.6 | 21.2980 | 4 | **19** | 2.0 | 23.1500 | 4 |
| **8** | 3.5 | 21.2980 | 4 | **20** | 4.2 | 23.1500 | 4 |
| **9** | 5.9 | 21.2980 | 2 | **21** | 3.0 | 22.2240 | 1 |
| **10** | 5.4 | 22.2240 | 4 | **22** | 2.2 | 18.5200 | 8 |
| **11** | 2.1 | 22.2240 | 4 | **23** | 4.8 | 21.2980 | 1 |
| **12** | 4.7 | 22.2240 | 1 | **24** | 4.9 | 21.2980 | 2 |

## 6. CASE STUDY

In this section, the monitoring system and the different rescheduling strategies are applied in simulation to vessels sailing through the Guadalquivir waterway, a 87 km natural waterway located in the south of Spain. This waterway is divided into a total of $Z = 24$ sections, and hence, there are a total of 25 boundaries. Each of these sections $p$ is characterised by its length $d_p$, the maximum speed at which vessels can sail through it $\mu_p$, and its width $w_p$. The values of these parameters are detailed in in Table 1. Note that the width of each section, rather than its real measure, receives a value contained in the discrete set $\{2, 4, 8\}$. To analyze the proposed approach, different experiments have been carried out under randomly generated scenarios. All optimization problems have been solved using Gurobi solver. Each scenario is defined by the sequence of arrival times, $t_i^r$. This times are obtained following a Poisson distribution with characteristic parameter $\lambda$, starting both sequences at time $t^{init}$. The vessels' beams are categorized into three categories: small, medium or large. These categories are quantified as 1, 2 and 4, respectively. An uniform distribution is employed to select the beam of each vessel. We consider arrival delays and speed reduction incidents.

For the case of arrival delay incident scenarios, each vessel is affected by an arrival delay incident with probability $p_{delay}$. A random arrival delay following an uniform distribution between 0.5 h and 1 h is applied. For the case of

Table 2. Accidents as a function of $p_{delay}$.

| $p_{delay}$ | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 |
|---|---|---|---|---|---|
| Number of accidents | 1.20 | 2.74 | 3.58 | 4.34 | 4.44 |

Table 3. Accidents as a function of $p_{speed}$.

| $p_{speed}$ | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 |
|---|---|---|---|---|---|
| Number off accidents | 1.46 | 3.15 | 4.66 | 6.01 | 7.37 |

arrival delay incidents scenarios, each vessel is affected by a speed reduction incidents with probability $p_{speed}$. The maximum speed at which each vessel can sail is multiplied by a factor $\delta_i$, which is randomly generated following an uniform distribution between 0.5 and 0.9. The time instant when the incident is applied is randomly selected following an uniform distribution.

To show the necessity of rescheduling, a series of experiments have been carried out to analyze how the number of accidents in the waterway increases with the probability of suffering an arrival delay or speed reduction incident. An accident occurs if two vessels encounter each other in a section of the waterway whose width is not greater or equal than the sum of their beams.

For the case of arrival delay incidents, 100 scenarios for $N = 8$ and $\lambda = 0.05$ h have been generated for different values of $p_{delay}$ between 0.1 and 0.9. For each scenario, the scheduling problem is solved, and an optimal trip plan is obtained for each vessel. Then, a simulation is carried out in which vessels sail at constant speed to cross each boundary at the time indicated by its trip plan. We assume that vessels that arrive with delay sail at the speed given by the original trip paln. The average number of accidents as a function of $p_{delay}$ is reflected in Table 2.

For the case of arrival delay incidents, 100 scenarios for $N = 8$ and $\lambda = 0.05$ h have been generated for different values of $p_{speed}$ between 0.1 and 0.9. For each scenario, the scheduling problem is solved, and an optimal trip plan is obtained for each of the vessels. Then, a simulation is carried out in which vessels sail at constant speed to cross each boundary at the time indicated by its trip plan. We assume that the vessel affected by the the incident sails at each section at the minimum of the original trip plan speed and its new maximum speed. The average number of accidents as a function of $p_{speed}$ is reflected in Table 3. The results show that the average number of accidents grows with the probability of arrival delay and speed reduction incidents.

Incidents are detected using the information provided by the AIS system comparing in real time the current location of each vessel, $z_i^\dagger$, with its expected location according to its optimal trip plan, $z_i(t)$. If the difference is greater than a certain threshold $\epsilon_z$, which in this case has been set to $\epsilon_z = 5$ km/10, an incident is detected. Figure 4 shows the expected trajectory and speed of a vessel according to its optimal trip plan (blue lines) and the real trajectory and speed applied taking into account a speed reduction incident at time 120 that reduces its maximum speed with $\delta_i = 0.5$ (red lines). The incident occurs at time 120, but it is not until time 127 that the incident is detected, that is, the detection time gap results to be 7 h/10.

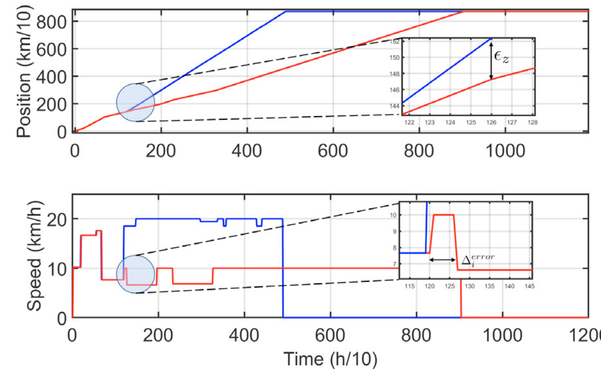


Fig. 4. Example of incident detection.

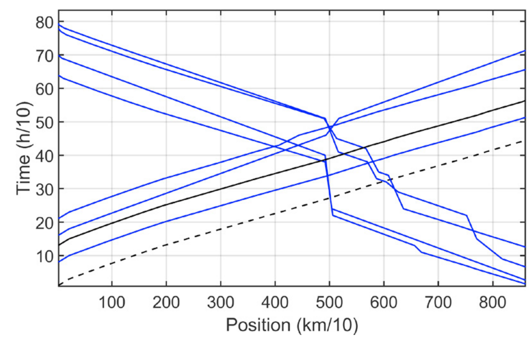


Fig. 5. Isolated rescheduling for an arrival delay incident.

Next we carried out simulations to demonstrate how the monitoring system works together with the rescheduling strategy. For each simulation, $N = 8$ vessels and $\lambda = 0.5$ h are considered. In the case of arrival delay incidents, a random delay between 0.5 h and 1 h is applied to the first vessel arriving to the waterway. On the other hand, for speed reduction incidents, the first vessel arriving to the waterway is affected by a speed reduction incident at a time randomly selected between the first hour of navigation with a speed reduction factor randomly selected between 0.5 and 0.9. In all cases, $\epsilon_z = 5$ km/10. Examples of different scenarios are shown in Figures 5-8 for both arrival delay and speed reduction incidents and for both isolated and global rescheduling strategies. In these figures, the dotted red lines represent the expected trajectories. The continuous blue lines represent the trajectories after rescheduling is performed. The dotted black lines represent the expected trajectories of the affected vessel. The continuous black line represents its trajectory after rescheduling is performed.

To demonstrate the trade-off between the sailing and rescheduling costs, a total of 100 scenarios with $N = 8$, $\lambda = 1$ and $\epsilon_z = 5$ km/10 have been generated for each type of incident. For each scenario, a total of 6 different simulations are carried out, each one applying a different rescheduling strategy: isolated rescheduling, global re-schedule, and multi-objective rescheduling for different values of $\eta$ ranging from 0.1 to 1000. The results of each simulation, if feasible, are the number of vessels affected and the absolute deviations between the arrival times to the final destination given by the original and the rescheduled plans. We consider that a vessel is affected by rescheduling if this quantity is greater than 2 h/10.

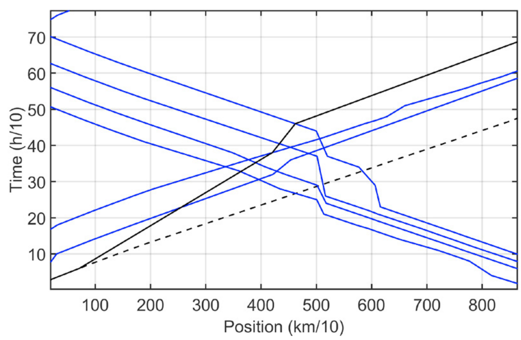


Fig. 6. Isolated rescheduling for a speed reduction incident.

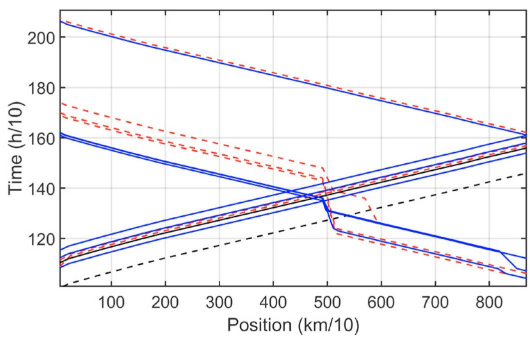


Fig. 7. Global rescheduling for an arrival delay incident.

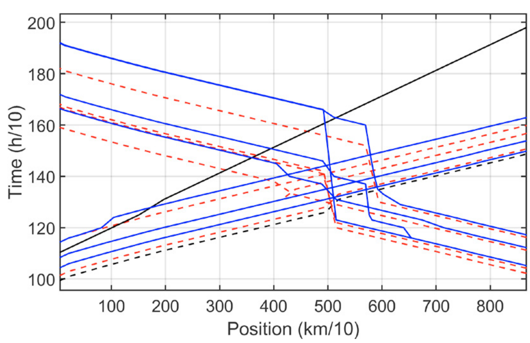


Fig. 8. Global rescheduling for a speed reduction incident.

In the case of arrival delay incidents (A.D.I), the first vessel arriving to the waterway is affected by an arrival delay incident with a random delay between 1 h and 3 h. The mean results obtained are shown in Table 4. As it can be appreciated, the average number of vessels affected (N.V.A) by rescheduling and the average difference between arrival times are lower and upper bounded by the number of vessels affected when isolated and global rescheduling strategies are applied, respectively.

For speed reduction incidents (S.R.I), the same procedure is applied. In this case, the first vessel arriving to the waterway is affected by a speed reduction incident during the first 1 hour of navigation and its maximum speed is reduced by a factor $\delta_i = 0.6$. The mean results obtained are shown in Table 4. As it can be appreciated, the average number of vessels affected and the average difference between arrival times are lower and upper bounded by the number of vessels affected when isolated and global rescheduling strategies are applied.

| | **A.D.I** | | **S.R.I** | |
|---|---|---|---|---|
| | $\lvert t^{\dagger}_{i,d} - t_{i,d}\rvert$ | N.V.A | $\lvert t^{\dagger}_{i,d} - t_{i,d}\rvert$ | N.V.A |
| Global | 6.05 | 4.94 | 6.87 | 3.97 |
| M.O ($\eta = 0.1$) | 4.63 | 4.59 | 6.20 | 3.26 |
| M.O ($\eta = 1$) | 3.64 | 4.25 | 5.56 | 2.82 |
| M.O ($\eta = 10$ ) | 3.37 | 3.74 | 5.27 | 2.67 |
| M.O ($\eta = 100$) | 3.21 | 3.44 | 4.63 | 2.48 |
| M.O ($\eta = 1000$) | 2.98 | 3.06 | 4.28 | 2.12 |
| Isolated | 0.91 | 1 | 4.07 | 1 |

Table 4. Vessels affected by rescheduling

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