Dynamic Coordination of Multiple Movable Bridges and Vessels for Time-Efficient Inland Waterway Navigation

Pablo Segovia, Vicenç Puig, Rudy R. Negenborn and Vasso Reppa

***Abstract*—This paper considers the presence of movable bridges in inland waterway transport, and presents a control framework for the joint dynamic coordination of bridge operations and autonomous vessel navigation to minimize waiting times of vessels at bridges. Simultaneous evolution of bridge occupancy and vessel position is captured by a control-oriented model that incorporates qualitative behavior in the form of propositional logic expressions. A model predictive control (MPC) strategy is designed considering adaptable bridge opening regimes to exploit vessel passage demand, and operational preferences of both vessel skippers and bridge operators are taken into account to reach fair trade-off decisions. A realistic case study pertaining to the Rhine-Alpine corridor is used to demonstrate the effectiveness of the approach. Appropriate key performance indicators (KPIs) are defined and employed for a quantitative comparison with a mixed-integer programming (MIP) strategy with fixed opening regimes. Furthermore, sensitivity to the main MPC parameters is examined by carrying out extensive testing to assess the effect of each design parameter on the solution.**

***Index Terms*—Inland waterway transport, movable bridges, model predictive control, propositional logic, multi-objective optimization.**

NOMENCLATURE

α, β	weighting factors
$\mathcal{B}$	set of movable bridges
$b^{(i)}$	nominal width of bridge i
H_p	prediction horizon
J_k	value of cost function at time step k
$\mathcal{K}$	set of time steps
k	current time step
$m\,(m_k)$	cardinality of set $\mathcal{V}\,(\mathcal{V}_k)$
$N_{\text{up}}^{(i)}, N_{\text{down}}^{(i)}$	maximum up-time and minimum down-time of bridge i
n	cardinality of set $\mathcal{B}$
$s_k^{(i)}$	opening status of bridge i at time step k
$\tau_e^{(i,j)}, \tau_o^{(i,j)}$	earliest and optimal passage time steps of vessel j through bridge i
$u_k^{(i,j)}$	control decision for bridge i, vessel j and time step k
$\mathcal{V}\,(\mathcal{V}_k)$	set of vessels to be scheduled (at time step k)
$v^{(j)}$	width of vessel j
$x_k^{(i)}$	width occupancy of bridge i at time step k
$\omega_k^{(j)}$	relative position of last bridge and vessel j at time step k
$z_k^{(i,j)}$	relative position of bridge i and vessel j at time step k

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I. INTRODUCTION

GLOBAL shipping and trade have experienced an exponential growth in the last years, up until the oil and commodity price crash in 2015 [1], leading to stringent demands on reducing transport-related costs and emissions. In this context, inland waterway transport (IWT) has emerged as an efficient and sustainable alternative to road transport [2]. However, IWT only accounted for 4% of the cargo moved in the European Union in 2016 [3].

IWT is characterized by the operation of infrastructure—which typically includes locks and (movable and fixed) bridges—and vessels in confined spaces. Vessels pass locks and bridges while sailing along natural rivers and artificial canals characterized by limited draft and space for complex vessel manoeuvres [4], [5], [6]. These structures tend to become navigation bottlenecks [7] and delay vessel journeys, hence diminishing the confidence of end users in the efficiency of this transport mode [8]. This situation may be further aggravated by infrastructure maintenance operations [9].

Solutions to this problem can be examined from different perspectives. On the one hand, increasing infrastructure capacity might alleviate the problem. However, environmental and spatial limitations often hinder its applicability, not to mention the hefty infrastructure upgrade costs. On the other hand, the existing resources can be utilized in an optimal manner to maximize efficiency of operations. The latter option has become an active research topic as testified by the large body of literature. In particular, significant effort has been devoted to the *lock scheduling* problem, which requires to assign vessels to lock chambers, place vessels inside chambers, and schedule lockage operations [10]. A large variety of settings have been considered, e.g., individual locks [11], [12], and serial single-chamber [13], [14] and multiple-chamber [15], [16] lock configurations. Oddly enough, joint coordination of vessel navigation and bridge operations is, to the best knowledge of the authors, a problem that has received no attention despite the effect their operation has on waterborne, road and railway traffic. Instead, research on this topic has focused on the bridge part, e.g., design [17] and maintenance [18], while the vessel-bridge interplay has been ignored.

In view of this research gap, and aiming to contribute towards the improvement of IWT with a solution that reduces waiting time of vessels at movable bridges—and therefore travel time—a mixed-integer programming (MIP) approach was proposed in [19]. This strategy considered fixed bridge opening timetables, hence real-time vessel passage demand could not be exploited to optimize bridge movements.

The aforementioned limitation is overcome in this paper by considering adaptable bridge opening regimes to align bridge opening periods with optimal vessel passage plans, hence reducing waiting times. Operation of vessels and bridges can be coordinated by introducing vessel-to-infrastructure (V2I), infrastructure-to-vessel (I2V) and infrastructure-to-infrastructure (I2I) communication [20]. Infrastructure authorities, which act as the coordinator, receive and combine vessel voyage plans, provided by vessel skippers, with information provided by bridge operators to determine optimal vessel and bridge operation for overall optimal performance [19], [21]. Decisions made by the coordinator with regard to final vessel passage plans and bridge openings can then be provided to vessel skippers and bridge operators, respectively. The proposed solution, which was partially delineated in [22], is based on model predictive control (MPC) to determine optimal bridge opening periods and vessel position evolution simultaneously. MPC encompasses a range of relatively simple yet powerful control methods that use a model of the process to predict the effect of control inputs—determined as the solution of an optimization problem—on the system [23]. The interest in using MPC lies in the fact that their features align very well with the problem at hand. Information regarding future vessel passage demands can be exploited by the predictive nature of MPC. Physical constraints (e.g., maximum width availability of bridges) as well as operational constraints (e.g., maximum up-times and minimum down-times of bridges) can be naturally incorporated into the design. The preferences of vessel skippers and bridge operators—which are likely to be conflicting—can be used to define the cost function to be optimized, thereby influencing the solution. The effect of control actions can be used to make future decisions with updated information by virtue of the closed-loop nature of MPC. These reasons have fostered the adoption of MPC to address a large variety of problems, e.g., railway traffic management [24], [25], traffic flow control [26], [27], [28], [29], autonomous vessel control [30], [31], [32], and intermodal [33] and synchromodal [34] freight transport planning.

As mentioned in the previous paragraph, central to MPC is a model that allows to predict the effect of decisions on the system. It is good to note that the word *system* encompasses, in the context of this problem, all bridges that are inside the waterway of interest, and all vessels that must still pass through at least one of these bridges. Therefore, important information from both kinds of agents must be captured by this model. In addition to quantitative models to describe, e.g., amount of bridge width that vessels use during their passage, qualitative information from the vessel-bridge interplay is also available, which exists in the form of logical relationships among variables [35], e.g., vessel position and bridge status. Such qualitative behavior can be incorporated into the problem by stating this information using propositional logic, which can then be translated into linear constraints using integer variables [36]. This modeling approach has been successfully applied to diverse transportation problems, e.g., scheduling of infrastructure maintenance operations [37], route planning operations for autonomous vehicles [38], public bus transport operations [39], timetabling problems for rail networks [40], and path planning for automated guided vehicles [41].

Compared to the previous work of the authors [22], this article presents an improved control-oriented model and MPC formulation, considers the preferences of the two most relevant groups of stakeholders for the problem at hand, and features a quantitative in-depth performance assessment of the approach. More specifically, the main contributions are:

1) Improved derivation of some propositional logic expressions and the control-oriented model in Section III-B.
2) Consideration of the preferences of vessel skippers and bridge operators in Section IV-A, which allows to build a cost function that can yield fair trade-off decisions.
3) Extension of the MPC presented in Section IV-B due to the multi-objective nature of the control problem when multiple operational objectives are considered.
4) Inclusion of a detailed, two-step assessment of the effectiveness of the proposed approach in Section V. First, the quality of the solution obtained using the proposed approach is determined using appropriate key performance indicators (KPIs), and the values are compared to those obtained using the strategy presented in [19]. Then, sensitivity to the main MPC parameters is examined by carrying out extensive testing to assess the effect of each design parameter on the solution.

The remainder of this paper is organized as follows. Section II describes the inland waterway transport problem considering movable bridges, and outlines a solution to address the problem that allows for adaptable bridge opening regimes. A control-oriented model is derived in Section III, which is then employed in the MPC designed in Section IV. Section V introduces a case study based on the Rhine-Alpine corridor to test the proposed approach. Two types of results are then presented and discussed on the basis of KPIs: a comparison between the adaptable and fixed opening regime approaches, and a sensitivity analysis to the main MPC parameters. Conclusions and future research directions are given in Section VI.

II. PROBLEM STATEMENT

The IWT problem in the presence of movable bridges is concerned with determining bridge opening periods and vessel position evolution in a coordinated manner, as clearance under bridges—measured from water surface to bridge underside—is not sufficient for vessels to sail below closed bridges. This is a non-trivial problem given the constraints imposed by limited bridge width availability for vessel passage, limitations on opening and closing periods, and earliest passage of vessels through bridges given both waterway and vessel speed limits. The problem of determining a solution that simultaneously satisfies vessel skippers and bridge operators is further aggravated by the conflicting nature of the preferences of both parties. While vessel skippers wish to fulfill their optimal travel plans as much as possible, bridge operators prefer to limit bridge status switches, i.e., open-close and close-open.

The problem can be formally stated as follows. A set of vessels, denoted with $\mathcal{V}$, must pass through a set of movable bridges, denoted with $\mathcal{B}$, on their way towards the destination, with $|\mathcal{B}| = n$ and $|\mathcal{V}| = m$, where $|\cdot|$ denotes set cardinality. A discrete problem setting is adopted, i.e., time is divided into a set of time steps $\mathcal{K}$ of equal length. Moreover, bridges and vessels are characterized by the following data:

- Bridge i, $i \in \{1, ..., n\}$, is defined by its nominal width, $b^{(i)}$ [m], the maximum number of consecutive time steps it can stay open (traffic disruption duration on the bridge deck is upper-bounded), $N_{\text{up}}^{(i)}$, and the minimum number of consecutive time steps it must remain closed immediately after closing, $N_{\text{down}}^{(i)}$, $\forall i \in \mathcal{B}$. Note that N_{up} and N_{down} are usually referred to in the literature as *maximum up-time* and *minimum down-time*, respectively. Furthermore, bridges are numbered in such manner that $i = 1$ and $i = n$ denote the first and last bridge to be passed through, respectively. The reason is that all vessels are considered to sail between the two same endpoints, entering the waterway through the same source node (before the first bridge) and leaving it at the same sink node (after the last bridge).
- Vessel j, $j \in \{1, ..., m\}$, is defined by its width, $v^{(j)}$ [m] (which includes the safety distance between vessel j and other vessels), and its voyage plans, given by its earliest and optimal passage time steps through bridge i, $\tau_e^{(i,j)}, \tau_o^{(i,j)} \in \mathbb{Z}_+$, respectively, $\forall i \in \mathcal{B}, \forall j \in \mathcal{V}$, with $\mathbb{Z}_+$ the set of positive integers. Earliest and optimal passage time steps can be determined from the maximum vessel speed and the speed that minimizes fuel consumption, respectively, and inter-bridge distances. These values are assumed to be known before the start of the journey. Note that vessels can enter the waterway at any time step $k \in \mathcal{K}$, and are no longer taken into consideration once they have passed through the n bridges.

The solution is given by the set of binary decisions $u_k^{(i,j)}$:

$$u_k^{(i,j)} = \begin{cases} 1 & \text{if vessel } j \text{ is assigned to pass} \\ & \text{bridge } i \text{ at time step } k, \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

The quality of the solution is quantitatively assessed using the following KPIs:

1) Percentage of vessels assigned to pass at their optimal passage time, i.e., $\tau_o^{(i,j)}$.
2) Number of bridge status switches.
3) Minimum, average and maximum relative bridge width occupancy (during opening time steps).

The first and second KPIs indicate how well the solution aligns with the preferences of vessel skippers and bridge operators, respectively. On the other hand, while the last KPI does not reflect directly the preference of any type of agent, it is a resource usage indicator—the resource being bridge width for vessel passage.

The proposed approach is divided into two parts. A control-oriented model is derived in Section III. This model is then employed in the model-based predictive control strategy designed in Section IV. Then, relevant decisions for each vessel and each bridge can be communicated to the corresponding vessel skipper and bridge operator, respectively.

III. Control-oriented modeling approach

The goal of this section is to develop a model that can be used for the dynamic coordination of vessel and bridge operations. This model consists of two parts. The occupancy model, which describes the evolution of both bridge width availability for vessel passage and vessel position, is introduced first. The second part of the model consists of logical rules that govern the proper evolution of system variables. These rules are first stated in the form of propositional logic expressions and then converted into (in)equality constraints. The section is concluded with an illustrative example and some notes on the applicability of the approach to consider river structures other than movable bridges, i.e, locks.

A. The occupancy model

Bridge occupancy can be defined as the total bridge width that vessels require to sail through at each time step. This physical quantity constitutes a limited resource that must be suitably allocated among vessels to satisfy optimal vessel travel plans, given by $\tau_o^{(i,j)}$, as much as possible.

Width occupancy evolution of bridges is given by

$$x_{k+1}^{(i)} = x_k^{(i)} + \underbrace{\sum_{j \in \mathcal{V}_k^{(i)}} v^{(j)} u_k^{(i,j)}}_{\text{current resource booking}} - \underbrace{\sum_{j \in \mathcal{V}_{k-1}^{(i)}} v^{(j)} u_{k-1}^{(i,j)}}_{\text{delayed resource release}}, \tag{2}$$

where $x_k^{(i)} \in \mathbb{R}$ [m] represents the width occupancy of bridge i at time step k, $\forall i \in \mathcal{B}, \forall k \in \mathcal{K}$.

Equation (2) represents a width occupancy balance, such that the current occupancy of bridge i, i.e., $x_k^{(i)}$, increases at the next time step, i.e, $x_{k+1}^{(i)}$, as a consequence of decisions $u_k^{(i,j)} = 1$, $\forall j \in \mathcal{V}_k^{(i)}$, thus allowing for multiple vessels to pass a bridge simultaneously (as long as their combined width does not exceed bridge width). However, passage of a vessel through a bridge is assumed to be done in a single time step. Therefore, inclusion of delayed control actions $u_{k-1}^{(i,j)}$, which were determined as the solution of the control problem at the previous time step $k-1$, represents resource release to reset bridge width occupancy. In other words, every vessel passing through a bridge is allocated a certain amount of bridge width for passage only during one time step. Time step size is chosen sufficiently large so that vessel i passes through bridge j in one time step with zero dwell time, $\forall i \in \mathcal{B}, \forall j \in \mathcal{V}$. This also allows to consider that bridges are either open or closed.

It is important to note that $\mathcal{V}$ is endowed with a temporal dimension in Equation (2), i.e., $\mathcal{V}_k$ and $\mathcal{V}_{k-1}$. As vessels may enter or leave the waterway at any time step, the number of vessels is time-varying. Then, the set of vessels to be considered at current time step k is denoted with $\mathcal{V}_k$, with $|\mathcal{V}_k| = m_k$. The term $\mathcal{V}_k$ can be decomposed into non-overlapping subsets $\mathcal{V}_k^{(i)}$ such that $\mathcal{V}_k = \bigcup_{i=1}^{n} \mathcal{V}_k^{(i)}$, with $\mathcal{V}_k^{(i)} \triangleq \left\{ j : z_k^{(i,j)} = 1 \right\}, \forall i \in \mathcal{B}, \forall k \in \mathcal{K}$.

The variable $z_k^{(i,j)}$ is introduced to indicate vessel positions within the waterway in a descriptive manner. More precisely, $z_k^{(i,j)}$ indicates the next bridge to be passed by vessel i, $\forall i \in \mathcal{B}, \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K}$, and is defined as follows:

$$z_k^{(i,j)} = \begin{cases} 1 & \text{if bridge } i \text{ is the next bridge en} \\ & \text{route for vessel } j \text{ at time step } k, \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

The difference between $u_k^{(i,j)}$ and $z_k^{(i,j)}$ is that $z_k^{(i,j)} = 1$ simply indicates that vessel j *can* pass through bridge i at time step k, while $u_k^{(i,j)} = 1$ implies that vessel j *does* pass through bridge i at time step k, $\forall i \in \mathcal{B}, \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K}$.

Two additional variables $\omega_k^{(j)}$ and $s_k^{(i)}$ are introduced to provide a more comprehensive representation of bridge-vessel operations. On the one hand, $\omega_k^{(j)}$ indicates whether vessel j has been assigned a passage time through the last bridge before the destination, $\forall j \in \mathcal{V}_k^{(n)}$, and is defined as follows:

$$\omega_k^{(j)} = \begin{cases} 1 & \text{if vessel } j \text{ has been assigned a passage} \\ & \text{time through last bridge at time step } k, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

On the other hand, $s_k^{(i)}$ denotes whether bridge i is open or closed at time step k, and is defined as follows:

$$s_k^{(i)} = \begin{cases} 1 & \text{if bridge } i \text{ is open at time step } k, \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

B. Propositional logic expressions and equivalent constraints

In addition to the bridge occupancy model given by Equation (2), additional relationships between variables $u_k^{(i,j)}$, $x_k^{(i)}$, $z_k^{(i,j)}$, $\omega_k^{(j)}$ and $s_k^{(i)}$ must be established to ensure that bridge width occupancy and vessel position evolve properly, and logical incompatibilities are forbidden. For instance, suppose that $z_k^{(i,j)} = 1$ for a certain bridge i and vessel j at time step k. Then, the control algorithm must enforce $u_k^{(l,j)} = 0$ for $l \neq i$. As a side note, $u_k^{(i,j)}$ may or may not be set equal to 1 depending on the cost function and the rest of operational constraints, which are provided hereunder.

Manipulation of these propositional logic expressions allows to obtain constraints in the form of linear equations and (in)equalities [35], [36]. These logic expressions are first given as *if-then* clauses, then transformed into their equivalent conjunctive normal form as shown in [42, Eqs. (5)–(8)], and finally converted into linear (in)equalities as summarized in [42, Table 1]. The following logic rules can be stated for all bridges $i \in \mathcal{B}$, vessels $j \in \mathcal{V}_k$ and time steps $k \in \mathcal{K}$:

- If bridge i is not the next bridge en route for vessel j at time step k, then vessel j cannot pass through bridge i at time k. This can be formally stated as: $\left(z_k^{(i,j)} = 0\right) \rightarrow \left(u_k^{(i,j)} = 0\right)$. The equivalent constraint is

$$z_k^{(i,j)} - u_k^{(i,j)} \geq 0, \ \forall i \in \mathcal{B}, \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K}. \tag{6}$$

- At time step k, vessel j either has a single bridge to be passed next or has already been assigned a passage time through all bridges. This can be formally stated as: $\left(\sum_{i=1}^{n} z_k^{(i,j)}\right) \oplus \omega^{(j)}$, where $\oplus$ denotes the logical XOR operation. The equivalent constraint is

$$\sum_{i=1}^{n} z_k^{(i,j)} + \omega_k^{(j)} = 1, \ \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K}. \tag{7}$$

- If bridge i is the next bridge en route for vessel j at time step k and vessel j is not assigned to pass through bridge i at time step k, then bridge i will be the next bridge en route for vessel j at time step $k+1$. This can be formally stated as: $\left(\left(z_k^{(i,j)} = 1\right) \wedge \left(u_k^{(i,j)} = 0\right)\right) \rightarrow \left(z_{k+1}^{(i,j)} = 1\right)$. The equivalent constraint is

$$-z_k^{(i,j)} + u_k^{(i,j)} + z_{k+1}^{(i,j)} \geq 0, \ \forall i \in \mathcal{B}, \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K}. \tag{8}$$

- If vessel j is assigned to pass through bridge i at time step k and bridge i is not the last bridge, then bridge $i+1$ will be the next bridge en route at time step $k+1$. This can be formally stated as: $\left(u_k^{(i,j)} = 1\right) \rightarrow \left(z_{k+1}^{(i+1,j)} = 1\right)$. The equivalent constraint is

$$z_{k+1}^{(i+1,j)} - u_k^{(i,j)} \geq 0, \ \forall i \in \mathcal{B} \setminus \{n\}, \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K}. \tag{9}$$

- If vessel j is assigned to pass through bridge i at time step k and bridge i is the last bridge, then the scheduling of vessel j is complete at time step $k+1$. This can be formally stated as: $\left(u_k^{(i,j)} = 1\right) \rightarrow \left(\omega_{k+1}^{(j)} = 1\right)$. The equivalent constraint is

$$\omega_{k+1}^{(j)} - u_k^{(i,j)} \geq 0, \ i = n, \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K}. \tag{10}$$

- If $\tau_e^{(i,j)}$ is greater than time step k, then vessel j cannot be assigned to pass through bridge i at time step k. This can be formally stated as: $\left(k \leq \tau_e^{(i,j)} - 1\right) \rightarrow \left(u_k^{(i,j)} = 0\right)$. The equivalent constraint is

$$k \geq u_k^{(i,j)} \left(\tau_e^{(i,j)} - 1\right) + 1, \ \forall i \in \mathcal{B}, \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K}. \tag{11}$$

- Bridge i should only be open at time step k if and only if at least one vessel passes through bridge i at time step k. This can be formally stated as: $\left(s_k^{(i)} = 1\right) \leftrightarrow \left(\sum_{j \in \mathcal{V}_k^{(i)}} u_k^{(i,j)} \geq 1\right)$. The equivalent constraint is

$$s_k^{(i)} \leq \sum_{j=1}^{m_k} u_k^{(i,j)} \leq m_k s_k^{(i)}, \ \forall i \in \mathcal{B}, \forall k \in \mathcal{K}, \tag{12}$$

with m_k the number of vessels at time step k.

- If bridge i was open at time step $k-1$ and closes at k, then bridge i must remain closed during at least $N_{\text{down}}^{(i)}$ consecutive time steps. This can be formally stated as: $\left(s_{k-1}^{(i)} - s_k^{(i)} = 1\right) \;\rightarrow\; \left(s_l^{(i)} = 0\right)$. The equivalent constraint is

$$s_{k-1}^{(i)} - s_k^{(i)} \leq 1 - s_l^{(i)},\ \forall i \in \mathcal{B}, \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K}, \quad (13)$$

and $l = k, ..., \min\left(k + N_{\text{down}}^{(i)} - 1, T\right)$, where T is the horizon of the control problem. In receding horizon approaches such as the one considered in this paper, T equals the prediction horizon, denoted with H_p.
- If bridge i was closed at instant $k-1$ and opens at instant k, then bridge i can remain open during at most $N_{\text{up}}^{(i)}$ consecutive time steps. This can be formally stated as: $\left(s_k^{(i)} - s_{k-1}^{(i)} = 1\right) \;\rightarrow\; \left(\sum_{l=k}^{\min\left(k+N_{\text{up}}^{(i)}, H_p\right)} s_l^{(i)} \leq N_{\text{up}}^{(i)}\right)$. The equivalent constraint is

$$\left(\sum_{l=k}^{\min\left(k+N_{\text{up}}^{(i)}, H_p\right)} s_l^{(i)}\right) - N_{\text{up}}^{(i)} \leq 1 - \left(s_k^{(i)} - s_{k-1}^{(i)}\right),\ \forall i \in \mathcal{B}, \forall k \in \mathcal{K}. \quad (14)$$

Equations (11)–(14) arise from relationships between variables and inequalities. A tolerance ε and a lower (upper) bound c (C) must be introduced: ε may be set equal to 1 should the coefficients and variables be integers [43, p. 170], and c (C) can be computed as the lower (upper) bound [43, p. 171].

Furthermore, bridge width capacity must be observed:

$$0 \leq x_k^{(i)} \leq b^{(i)},\ \forall i \in \mathcal{B}, \forall k \in \mathcal{K}. \quad (15)$$

With all this, the second part of the control-oriented model is given by Equations (6)–(15).

C. Illustrative example and applicability of the approach

The scenario depicted in Figure 1 is used to illustrate how system variables (1)–(5) evolve while being subjected to the constraints given by Equations (6)–(15). Assume for now that optimal system operation is achieved when vessels pass bridges at $\tau_o^{(i,j)}$, $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{V}_k$, $\forall k \in \mathcal{K}$. Consider also the vessel and bridge parameter values that are summarized in Tables I and II, respectively, and initial states are set such that all vessels start their journey before the first bridge ($i = 1$) and must pass the two bridges. Then, decisions can be made according to vessel and bridge parameters, which make the system evolve in the following manner:

- $k = 1$: it is decided that the third, fourth and fifth vessels ($j = \{3, 4, 5\}$, respectively) will pass the first bridge, while no vessel will pass the second bridge. The decision to have the third vessel pass at $k = 1$ despite its optimal passage time is $k = 2$ comes from the fact that the simultaneous passage of the first ($j = 1$) and third vessels at $k = 2$ will not be not possible, as their combined width exceeds that of the first bridge, and that bridge will have to close at $k = 3$.

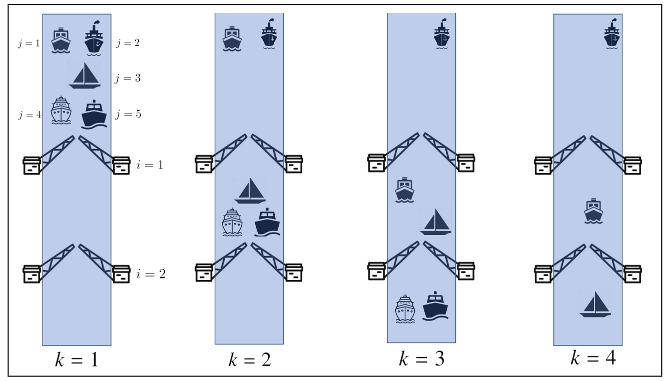

Fig. 1. Illustrative example of the coordinated operation of bridges and vessels

TABLE I
NUMERICAL VALUES OF VESSEL PARAMETERS

	$v^{(j)}[m]$	$\tau_e^{(i,j)}$	$\tau_o^{(i,j)}$
j=1	8	i=1: $\tau_e^{(i,j)} = 1$	i=1: $\tau_o^{(i,j)} = 3$
		i=2: $\tau_e^{(i,j)} = 2$	i=2: $\tau_o^{(i,j)} = 4$
j=2	6	i=1: $\tau_e^{(i,j)} = 1$	i=1: $\tau_o^{(i,j)} = 4$
		i=2: $\tau_e^{(i,j)} = 2$	i=2: $\tau_o^{(i,j)} = 6$
j=3	3	i=1: $\tau_e^{(i,j)} = 1$	i=1: $\tau_o^{(i,j)} = 2$
		i=2: $\tau_e^{(i,j)} = 2$	i=2: $\tau_o^{(i,j)} = 3$
j=4	5	i=1: $\tau_e^{(i,j)} = 1$	i=1: $\tau_o^{(i,j)} = 1$
		i=2: $\tau_e^{(i,j)} = 2$	i=2: $\tau_o^{(i,j)} = 2$
j=5	2	i=1: $\tau_e^{(i,j)} = 1$	i=1: $\tau_o^{(i,j)} = 1$
		i=2: $\tau_e^{(i,j)} = 2$	i=2: $\tau_o^{(i,j)} = 2$

TABLE II
NUMERICAL VALUES OF BRIDGE PARAMETERS

	$b^{(i)}$	$N_{up}^{(i)}$	$N_{down}^{(i)}$
i=1	10	2	2
i=2	8	2	2

- $k = 2$: it is decided that the first vessel will pass the first bridge, and the fourth and fifth vessels will pass the second and last bridge. The decision to have the first vessel pass at $k = 2$ despite its optimal passage time is $k = 3$ comes from the fact that the first bridge needs to close at that time since $N_{up}^{(1)} = 2$.
- $k = 3$: it is decided that the third vessel will pass the second bridge. The decision to have the third vessel pass the second bridge instead of the first vessel comes from the fact that their combined width exceeds that of the second bridge, and $\tau_o^{(2,3)} < \tau_o^{(2,1)}$. Moreover, the first bridge remains closed since since $N_{down}^{(1)} = 2$, hence the second vessel ($j = 2$) must wait until the bridge opens again. Furthermore, the fourth and fifth vessels are not even shown as they have passed all bridges.

It is important to stress out that a model-based approach is followed to illustrate system behavior by means of the previous example. This means that the variables and equations used to describe relevant system quantities depend on the river structures that are considered. While the case of movable bridges is specifically studied in this paper, the current

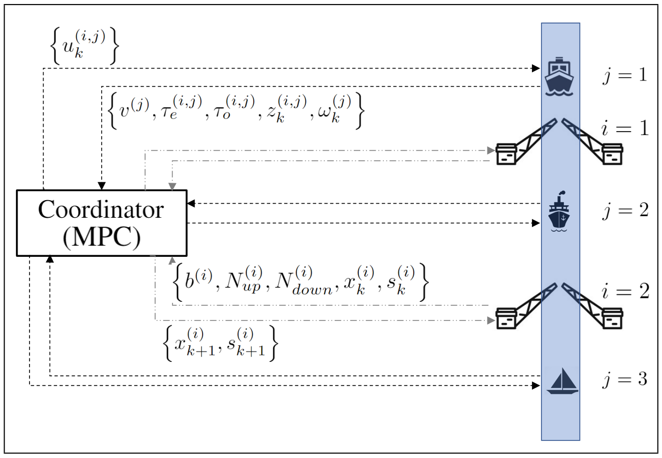

Fig. 2. Schematic representation of the proposed control architecture, including information exchanges

definition of variables allows to apply the approach to locks, which are other common river structures. The case of single-chamber locks requires no modification whatsoever of the model. On the other hand, the inclusion of multiple-chamber locks, which may be modeled considering one-dimensional chamber capacities as shown in [44, Ch. 4], requires slight modifications. If the i-th river structure is a lock equipped with l chambers, $u_k^{(i_l,j)}$ denotes the decision to have vessel j pass chamber l of lock i at time step k, $x_k^{(i_l)}$ represents the occupancy of chamber l of lock i at time step k, and $s_k^{(i_l)}$ represents the status of chamber l of lock i at time step k. Relative waterway position between vessels and locks can still be described using $z_k^{(i,j)}$ and $\omega_k^{(j)}$. Note that this redefinition of variables requires to adapt Equations (6)–(15) accordingly.

IV. An MPC approach for the IWT problem

The control-oriented model developed in Section III is used to design a control strategy with satisfactory performance. This control strategy is solved by a coordinator upon reception of relevant vessel and bridge information, as shown in Figure 2. Then, the solution of the control problem is communicated back to vessels and bridges in the form of decisions regarding final vessel passage plans and bridge openings, respectively.

The control problem that is solved by the coordinator is formulated as an MPC, which requires to define a set of operational objectives that are to be optimized subject to the control-oriented model. These objectives are described first. Then, the MPC is designed, and its implementation is outlined.

A. Operational objectives

Bridge opening and closing time slots and vessel passage times through bridges are determined as the solution of an optimization-based control problem, which means that the choice of cost function has a major effect on the solution. As these decisions affect both vessels and bridges, this function is chosen to be a weighted sum of two terms, each representing the preferences of vessel skippers and bridge operators.

On the one hand, vessel skippers wish for vessel passages through bridges with minimal passage error, defined as the difference between the optimal passage time and the passage decision. Quadratic errors are chosen to be penalized, which can be expressed as follows:

$$J_k^{(v)} = \sum_{i=1}^{n} \sum_{j=1}^{m_k} \left(k u_k^{(i,j)} - \tau_o^{(i,j)} \right)^2, \ \forall k \in \mathcal{K}. \tag{16}$$

Since $u_k^{(i,j)}$ is dimensionless, its direct comparison to $\tau_o^{(i,j)}$, which has discrete time units, is not possible, hence $u_k^{(i,j)}$ is multiplied by the discrete time step k. Then, $J_k^{(v)}$ is minimized when vessel j passes through bridge i at time step $k = \tau_o^{(i,j)}$, $\forall i \in \mathcal{B}, \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K}$.

On the other hand, bridge operators seek to minimize the number of bridge status switches, which shall reduce both energy consumption and infrastructure wear and tear. This can be mathematically expressed as

$$J_k^{(b)} = \sum_{i=1}^{n} \left(s_k^{(i)} - s_{k-1}^{(i)} \right)^2, \ \forall k \in \mathcal{K}. \tag{17}$$

The total cost function is then given by

$$J_k = \alpha J_k^{(v)} + \beta J_k^{(b)}, \ \forall k \in \mathcal{K}, \tag{18}$$

where α and β are the weighting factors. The effect of their values on the solution will be assessed in Section V-C1.

B. Control design and implementation

Constraints and objectives formulated in Sections III-B and IV-A, respectively, are used to formulate the MPC as

$$\min_{\left\{u_{l|k}^{(i,j)}\right\}_{l=k}^{k+H_p-1}} J\left(u_{l|k}^{(i,j)}\right) \tag{19}$$

subject to

$$\begin{aligned}
&\text{constraints (2), (6)–(15),} && \forall i \in \mathcal{B}, \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K},\\
&x_{k|k}^{(i)} = x_k^{(i)}, && \forall i \in \mathcal{B},\\
&z_{k|k}^{(i,j)} = z_k^{(i,j)}, && \forall i \in \mathcal{B}, \forall j \in \mathcal{V}_k,\\
&\omega_{k|k}^{(j)} = \omega_k^{(j)}, && \forall j \in \mathcal{V}_k,
\end{aligned}$$

with $\left\{u_{l|k}^{(i,j)}\right\}_{l=k}^{k+H_p-1} \triangleq \left\{u_{k|k}^{(i,j)}, u_{k+1|k}^{(i,j)}, \cdots, u_{k+H_p-1|k}^{(i,j)}\right\}$, where k, l and $k+l|k$ represent the current time step, the time step along the prediction horizon, and the predicted value of the variable at instant $k+l$ using information available at instant k, respectively. Then, in accordance with the MPC philosophy, only $u_{k|k}^{(i,j)}$ is applied. Problem (19) is solved again at the next time step, once the effect of $u_{k|k}^{(i,j)}$ on bridge width occupancy and vessel position is known.

The main implementation details of the MPC strategy are outlined in Algorithm 1, which is provided in Appendix A and complements the information provided in Figure 2, showing how information provided by vessels and bridges is processed by the coordinator. While this is not a necessary condition, all bridges are assumed to be completely available at the initial time step, i.e., all initial occupancies are assumed to be equal to zero, and all vessels must pass all bridges, starting with bridge $i = 1$. Moreover, as the set of vessels is time-varying, a new problem must be created at time step k for $\mathcal{V}_k$. This procedure is repeated until all vessels have been assigned a passage time through all bridges. Execution of Algorithm 1 concludes when this condition is met.

V. Case study

The case study described in [19], [22] is used to test the MPC. The waterway and the main features of vessels and bridges are described first. Then, the MIP approach with fixed opening regimes developed in [19] is briefly recalled and employed for comparison with the MPC using KPIs. Finally, a sensitivity analysis is conducted for the main MPC parameters, and results are provided in each case.

A. Waterway description

The Rhine-Alpine corridor connects the Rotterdam and Antwerp ports to the Mediterranean basin, all the while linking major European economic centers such as Brussels and Antwerp, the Randstad region, the Rhine-Ruhr and Rhine-Neckar regions, and Milan and Genoa. It is one of Europe's busiest freight routes, with a throughput that totals 19% of EU's total GDP [45].

The Beneden Merwede[1] is a stretch of the Rhine-Alpine corridor that flows between Dordrecht and Hardinxveld-Giessendam (the Netherlands), and is equipped with four movable bridges. Data regarding road and railway movable bridges are provided in Table III. Due to the small distance between the first and second bridge, these are treated as a single bridge, and thus the opening and closing actions for both bridges are considered equal.

Vessels sailing from Dordrecht to Hardinxveld-Giessendam must pass through the four bridges. Vessel widths are defined in accordance with the CEMT class of the stretch, and knowledge of both maximum vessel speeds and inter-bridge distances [46] is used to generate reasonable earliest and optimal bridge passage times.

B. Comparison of approaches with adaptable and fixed opening regimes

In order to better evaluate MPC performance, an alternative approach is used for comparison. Contrary to the current paper, a solution considering fixed bridge opening regimes was proposed in [19], which means the controller could neither adapt the opening regimes to vessel passage demand nor consider bridge operator preferences. Vessel passage times through bridges were then determined by solving an MIP problem, and computational burden was kept at bay by virtue of a rolling horizon implementation. Naturally, the same vessel and bridge data are used by both approaches, although some tunable MPC parameters, e.g., objective function weights and bridge opening regimes, do not appear explicitly in the approach with fixed opening regimes.

Application of Algorithm 1—coded using Matlab R2020b and YALMIP [47], and solved with Gurobi Optimization

[1] https://www.rijkswaterstaat.nl/water/vaarwegenoverzicht/beneden-merwede

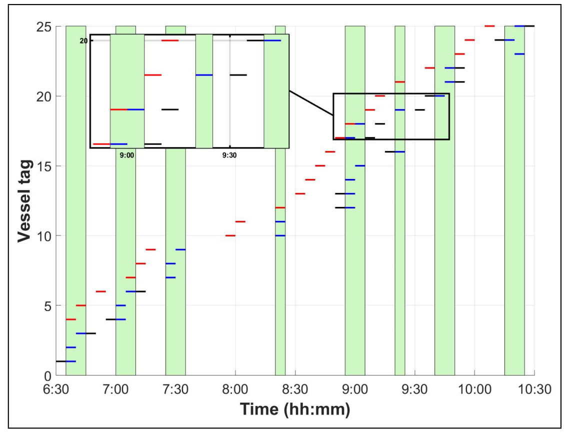

Fig. 3. Adaptable opening regime case, first and second bridges: $\tau_e^{(i,j)}$ (red), $\tau_o^{(i,j)}$ (black), $u_k^{(i,j)}$ (blue) and opening slots (green vertical bars)

9.1.2—allows to solve the case with adaptable regimes. The following values of the parameters are selected: weights $\{\alpha, \beta\} = \{1, 1\}$ (i.e., the objectives of vessel skippers and bridge operators are deemed to be equally important), prediction horizon $H_p = 30$ minutes, fleet size $\mathcal{V} = 25$, and maximum up-times $N_{\text{up}}^{(i)}$ and minimum down-times $N_{\text{down}}^{(i)}$ as in Table III. It is recalled that sensitivity to these parameters will be analyzed in Section V-C. Furthermore, a time step size of five minutes is selected, which is deemed appropriate given the inter-bridge distances in Table III and the maximum vessel speeds on the waterway [46]. While discrete times are represented using integers, these are converted into five-minute time intervals to facilitate result visualization and analysis.

Resulting vessel passage times through the first and second bridge, third, and fourth bridge are depicted in Figures 3, 4 and 5, respectively, and contain information of interest to both vessels skippers and bridge operators. On the one hand, time steps within vertical green bars—which are of uneven widths—fulfill the condition $s_k^{(i)} = 1$. On the other hand, $\tau_e^{(i,j)}$, $\tau_o^{(i,j)}$ and $u_k^{(i,j)}$ are depicted as red, black and blue horizontal bars, respectively, with widths equal to one time step, i.e., five minutes. If $u_k^{(i,j)}$ matches either $\tau_e^{(i,j)}$ or $\tau_o^{(i,j)}$, the overlap is resolved by plotting $u_k^{(i,j)}$. It can be observed that vessels are assigned passage times as close to the optimal values as possible while fulfilling all constraints. No vessel passes through a bridge before its earliest passage time or outside bridge opening timetables. Bridges are only open during the time steps vessels pass through bridges. Maximum up-times and minimum down-times given in Table III are respected. Moreover, Figure 6 shows that maximum bridge width occupancies are observed.

On the other hand, passage times and bridge width occupancies for the case with fixed regimes are depicted in Figures 7–9 and Figure 10, respectively. Earliest vessel passage times, bridge opening regimes and maximum width occupancies, and alignment of vessel passage with bridge opening windows are also observed by this solution. Constraints on maximum up-times and minimum down-times cannot be implemented in this approach due to the fixed opening setting.

Numerical values of the KPIs introduced in Section II

TABLE III
MOVABLE BRIDGES IN THE BENEDEN MERWEDE

Bridge (number and name)	Width [m]	Max. up-time [min]	Min. down-time [min]	Distance from previous bridge [m]
(1) Traffic bridge Dordrecht	44	10	15	–
(2) Railway bridge Grotebrug	44	10	15	50
(3) Traffic bridge Papendrecht	30	10	10	4500
(4) Railway bridge Baanhoek	30	15	5	2500

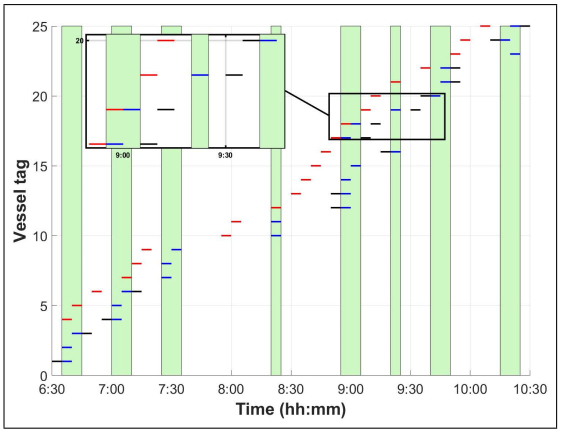

Fig. 4. Adaptable opening regime case, third bridge: $\tau_e^{(i,j)}$ (red), $\tau_o^{(i,j)}$ (black), $u_k^{(i,j)}$ (blue) and opening slots (green vertical bars)

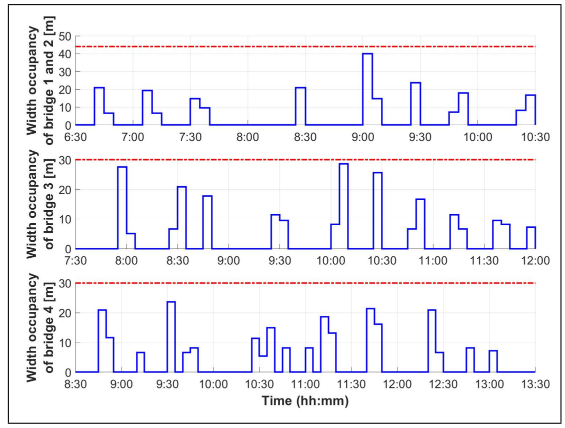

Fig. 6. Adaptable opening regime case, width occupancies

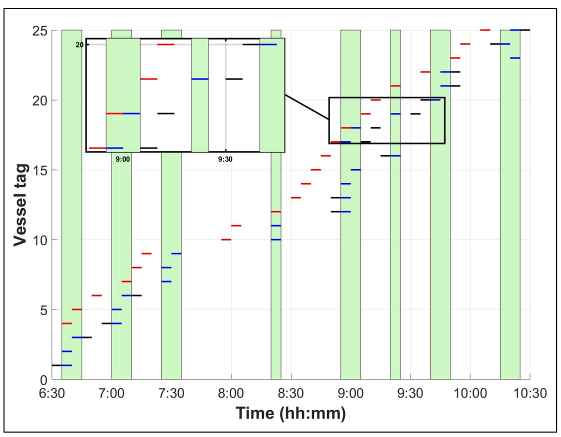

Fig. 5. Adaptable opening regime case, fourth bridge: $\tau_e^{(i,j)}$ (red), $\tau_o^{(i,j)}$ (black), $u_k^{(i,j)}$ (blue) and opening slots (green vertical bars)

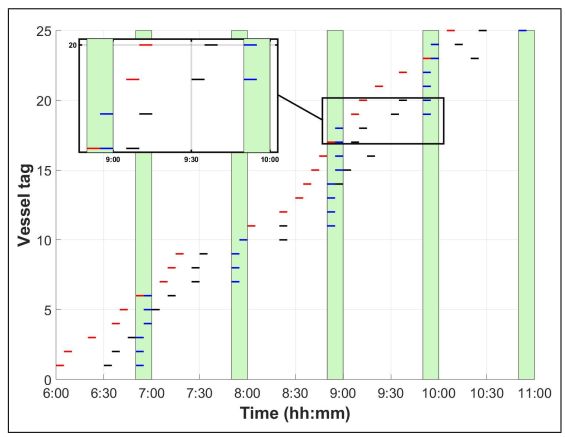

Fig. 7. Fixed opening regime case, first and second bridges: $\tau_e^{(i,j)}$ (red), $\tau_o^{(i,j)}$ (black), $u_k^{(i,j)}$ (blue) and opening slots (green vertical bars)

and computation times for both adaptable and fixed opening approaches are summarized in Table IV. On the one hand, the approach to solve the fixed opening regime case requires approximately 1.5 times more computation time to generate a complete solution than the adaptable opening regime case. While this significant increase is mainly due to different implementations, it should be noted that all problem instances are solved in less than five minutes (the discrete time step), thus fulfilling this key requirement for real-time decision making. On the other hand, the adaptable strategy benefits from the possibility to operate bridges according to vessel passage demand, a fact that can be realized upon inspection of the first KPI (the vessel passage at $\tau_o^{(i,j)}$ indicator). Twice as many vessels pass bridge 1 (B1) at their optimal passage time if the adaptable bridge opening regime approach is used instead of the fixed case (baseline approach). Moreover, as many as six times more vessels pass bridges 2 and 3 (B2 and B3, respectively) at their optimal passage time when the adaptable approach is used instead of the fixed approach. However, being able to operate bridges on demand is, as could be expected, a downside for bridge operators, since bridge status switches are much more frequent—at least 60% more frequent for the adaptable strategy compared to the fixed opening case. Regarding the last KPI, no significant differences in terms of minimum and maximum relative bridge width occupancy can be noticed. However, average occupancies are lower for adaptable MPC strategy, which is due to the increased number of opening windows (the number of vessels and their widths are the same in both approaches).

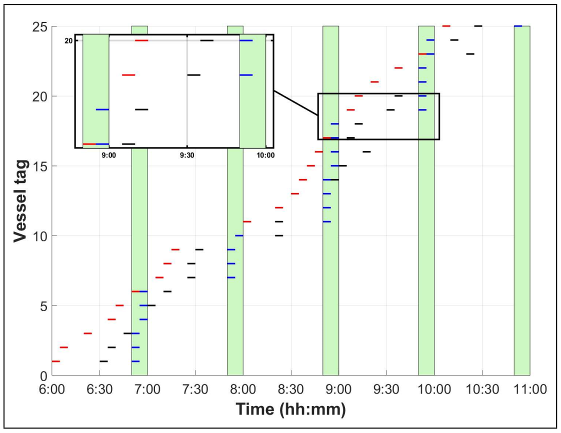

Fig. 8. Fixed opening regime case, third bridge: $\tau_e^{(i,j)}$ (red), $\tau_o^{(i,j)}$ (black), $u_k^{(i,j)}$ (blue) and opening slots (green vertical bars)

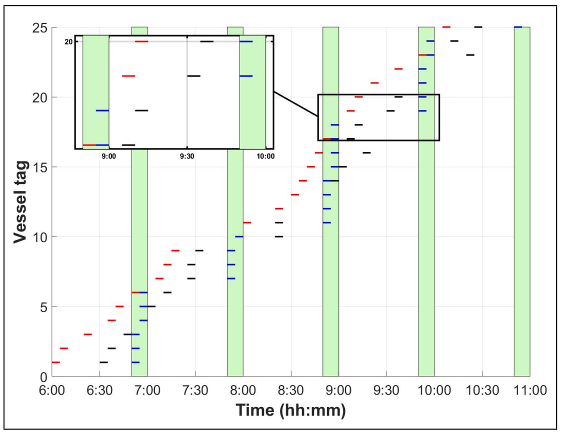

Fig. 9. Fixed opening regime case, fourth bridge: $\tau_e^{(i,j)}$ (red), $\tau_o^{(i,j)}$ (black), $u_k^{(i,j)}$ (blue) and opening slots (green vertical bars)

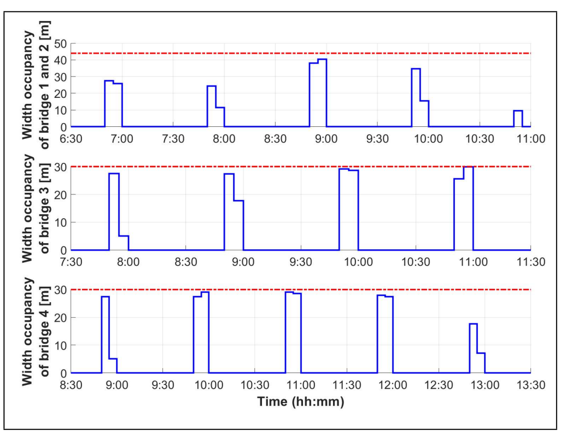

Fig. 10. Fixed opening regime case, width occupancies

C. Sensitivity analysis to the main MPC parameters

The adaptable opening strategy solution has been analyzed in detail in the previous subsection for one set of numerical parameter values. The objective of the present subsection is to perform a sensitivity analysis for the main parameters of the approach, i.e., weights α and β, prediction horizon, fleet size, traffic density profiles and bridge opening regimes. While the first two are MPC parameters, different fleet sizes, traffic density profiles and bridge opening regimes are bound to have a direct impact on the results. The same KPIs are computed for different values of one parameter, while the rest are kept constant. Then, direct comparison of KPIs allows to make informed decisions about the tuning of each parameter.

TABLE IV
KPIs FOR APPROACHES WITH ADAPTABLE AND FIXED OPENING REGIMES

	Computation time [s]	Vessel passage at $\tau_o^{(i,j)}$ [%]	Bridge status switches	{min., avg., max.} bridge width occupancy [%]
Adaptable	925.47	B1: 40 B2: 48 B3: 80	B1: 16 B2: 20 B3: 26	B1: {0.15, 0.37, 0.91} B2: {0.17, 0.45, 0.95} B3: {0.18, 0.42, 0.79}
Fixed	1386.43	B1: 20 B2: 8 B3: 12	B1: 10 B2: 10 B3: 10	B1: {0.22, 0,57, 0.92} B2: {0.17, 0.76, 1} B3: {0.17, 0.76, 0.97}

TABLE V
SENSITIVITY TO VALUES FOR VESSEL PASSAGE AT $\tau_o^{(i,j)}$ [%]

		β			
		1	10	100	1000
α	1	B1: 40 B2: 48 B3: 80	B1: 36 B2: 45 B3: 76	B1: 32 B2: 39 B3: 73	B1: 25 B2: 33 B3: 66
	10	B1: 40 B2: 53 B3: 82	B1: 40 B2: 48 B3: 80	B1: 36 B2: 45 B3: 76	B1: 32 B2: 39 B3: 73
	100	B1: 43 B2: 56 B3: 82	B1: 40 B2: 53 B3: 82	B1: 40 B2: 48 B3: 80	B1: 36 B2: 45 B3: 76
	1000	B1: 43 B2: 59 B3: 85	B1: 43 B2: 56 B3: 82	B1: 40 B2: 53 B3: 82	B1: 40 B2: 48 B3: 80

1) Objective function weights: Larger weights denote higher priority over the rest of objectives, as the optimization-based control problem is solved by minimizing the value of the objective function. Therefore, larger α-to-β ratios, where α and β are the weights assigned to vessel skipper and bridge operator objectives, respectively, are expected to result in more vessels seeing their optimal passage plans fulfilled. On the other hand, smaller α-to-β ratios are expected to result in less bridge status switches. Note also that different α-to-β ratios are not expected to affect computation times.

All combinations of the following values are tested for weights α and β: 1, 10, 100 and 1000. The rest of parameters take the following values: $H_p = 30$ minutes, $\mathcal{V} = 25$, normal traffic density profile and $N_{\text{up}}^{(i)}$ and $N_{\text{down}}^{(i)}$ are as in Table III. The corresponding values of the KPIs are summarized in Tables V–VII. Unsurprisingly, same α-to-β ratios lead to the same KPI values. As this ratio increases, more importance is given to fulfilling vessel skipper preferences, which aligns well with the fact that vessels assigned to pass at the optimal values increase (first KPI), and bridge status switches decrease (second KPI). Moreover, there is no clear pattern regarding the third KPI, although the values seem to decrease when ratio increases and vice versa, which makes sense as more (less) openings should lead to lower (higher) average usage. Finally, different values of weights result in the same computation times that were reported in Table IV.

2) Prediction horizon: Larger prediction horizons allow to predict the effect of decisions further in time, which comes at

TABLE VI
SENSITIVITY TO VALUES FOR BRIDGE STATUS SWITCHES

		β			
		1	10	100	1000
α	1	B1: 16	B1: 14	B1: 12	B1: 8
		B2: 20	B2: 18	B2: 14	B2: 10
		B3: 26	B3: 24	B3: 20	B3: 16
	10	B1: 16	B1: 16	B1: 14	B1: 12
		B2: 22	B2: 20	B2: 18	B2: 14
		B3: 28	B3: 26	B3: 24	B3: 20
	100	B1: 18	B1: 16	B1: 16	B1: 14
		B2: 24	B2: 22	B2: 20	B2: 18
		B3: 28	B3: 28	B3: 26	B3: 24
	1000	B1: 18	B1: 18	B1: 16	B1: 16
		B2: 26	B2: 24	B2: 22	B2: 20
		B3: 30	B3: 28	B3: 28	B3: 26

TABLE VII
SENSITIVITY TO VALUES FOR {MIN., AVG., MAX.} BRIDGE WIDTH OCCUPANCY [%]

		β			
		1	10	100	1000
α	1	B1: {0.15, 0.37, 0.91}	B1: {0.18, 0.40, 0.94}	B1: {0.22, 0.44, 0.96}	B1: {0.27, 0.52, 1}
		B2: {0.17, 0.45, 0.95}	B2: {0.20, 0.49, 0.98}	B2: {0.28, 0.55, 1}	B2: {0.37, 0.63, 1}
		B3: {0.18, 0.42, 0.79}	B3: {0.22, 0.47, 0.84}	B3: {0.28, 0.53, 0.90}	B3: {0.35, 0.60, 0.96}
	10	B1: {0.15, 0.36, 0.91}	B1: {0.15, 0.37, 0.91}	B1: {0.18, 0.40, 0.94}	B1: {0.22, 0.44, 0.96}
		B2: {0.14, 0.43, 0.94}	B2: {0.17, 0.45, 0.95}	B2: {0.20, 0.49, 0.98}	B2: {0.28, 0.55, 1}
		B3: {0.18, 0.40, 0.79}	B3: {0.18, 0.42, 0.79}	B3: {0.22, 0.47, 0.84}	B3: {0.28, 0.53, 0.90}
	100	B1: {0.13, 0.36, 0.89}	B1: {0.15, 0.36, 0.91}	B1: {0.15, 0.37, 0.91}	B1: {0.18, 0.40, 0.94}
		B2: {0.14, 0.43, 0.92}	B2: {0.14, 0.43, 0.94}	B2: {0.17, 0.45, 0.95}	B2: {0.20, 0.49, 0.98}
		B3: {0.18, 0.40, 0.79}	B3: {0.18, 0.40, 0.79}	B3: {0.18, 0.42, 0.79}	B3: {0.22, 0.47, 0.84}
	1000	B1: {0.13, 0.36, 0.89}	B1: {0.13, 0.36, 0.89}	B1: {0.15, 0.36, 0.91}	B1: {0.15, 0.37, 0.91}
		B2: {0.13, 0.40, 0.76}	B2: {0.14, 0.43, 0.92}	B2: {0.14, 0.43, 0.94}	B2: {0.17, 0.45, 0.95}
		B3: {0.17, 0.37, 0.77}	B3: {0.18, 0.40, 0.79}	B3: {0.18, 0.40, 0.79}	B3: {0.18, 0.42, 0.79}

TABLE VIII
SENSITIVITY TO PREDICTION HORIZON

		Computation time [s]	Vessel passage at $\tau_o^{(i,j)}$ [%]	Bridge status switches	{min., avg., max.} bridge width occupancy [%]
Hp (min.)	30	925.47	B1: 40	B1: 16	B1: {0.15, 0.37, 0.91}
			B2: 48	B2: 20	B2: {0.17, 0.45, 0.95}
			B3: 80	B3: 26	B3: {0.18, 0.42, 0.79}
	60	5944.82	B1: 52	B1: 18	B1: {0.15, 0.40, 0.73}
			B2: 52	B2: 26	B2: {0.17, 0.40, 0.95}
			B3: 72	B3: 28	B3: {0.17, 0.40, 0.85}
	120	9608.07	B1: 56	B1: 16	B1: {0.19, 0.40, 0.76}
			B2: 52	B2: 20	B2: {0.17, 0.49, 0.95}
			B3: 80	B3: 26	B3: {0.17, 0.43, 0.91}
	240	41983.93	B1: 56	B1: 18	B1: {0.15, 0.47, 1}
			B2: 64	B2: 20	B2: {0.05, 0.37, 1}
			B3: 92	B3: 28	B3: {0.17, 0.41, 0.79}

TABLE IX
SENSITIVITY TO FLEET SIZE

		Computation time [s]	Vessel passage at $\tau_o^{(i,j)}$ [%]	Bridge status switches	{min., avg., max.} bridge width occupancy [%]
Fleet size	10	302.91	B1: 60	B1: 8	B1: {0.15, 0.29, 0.48}
			B2: 50	B2: 8	B2: {0.17, 0.49, 0.92}
			B3: 80	B3: 12	B3: {0.17, 0.37, 0.70}
	25	925.47	B1: 40	B1: 16	B1: {0.15, 0.37, 0.91}
			B2: 48	B2: 20	B2: {0.17, 0.45, 0.95}
			B3: 80	B3: 26	B3: {0.18, 0.42, 0.79}
	50	6438.44	B1: 40	B1: 28	B1: {0.15, 0.42, 1}
			B2: 42	B2: 32	B2: {0.12, 0.50, 0.99}
			B3: 58	B3: 36	B3: {0.17, 0.45, 0.99}
	75	8684.15	B1: 36	B1: 40	B1: {0.11, 0.43, 1}
			B2: 36	B2: 50	B2: {0.09, 0.51, 0.99}
			B3: 49	B3: 56	B3: {0.17, 0.46, 0.94}

the expense of increased computational times due to the larger size of the problem. However, while fulfillment of optimal vessel passage plans is expected to increase as a consequence of the availability of a larger amount of optimal vessel plans, its effect on number of bridge status switches and resource usage is hard to anticipate.

The following values are tested for H_p: 30, 60, 120 and 240 minutes. The rest of parameters take the following values: $\{\alpha, \beta\} = \{1, 1\}$, $\mathcal{V} = 25$, normal traffic density profile and $N_{\text{up}}^{(i)}$ and $N_{\text{down}}^{(i)}$ are as in Table III. The corresponding values of the KPIs are summarized in Table VIII. As it could be anticipated, larger prediction horizons lead to sharp increases in computation times, as the algorithm must compute decisions further ahead. As a consequence of this, passage decisions at optimal values increases (first KPI), which is due to the fact that the algorithm is provided an increased number of future optimal voyage plans. Moreover, there are no significant differences or discernible trends in terms of bridge status switches (second KPI). Likewise, there is no clear pattern in terms of bridge width utilization (third KPI).

3) Fleet size: Larger fleet sizes result in a larger amount of decisions $u_k^{(i,j)}$ to be determined. As such, computational times are also expected to increase. On the other hand, larger fleet sizes are expected to decrease fulfillment of optimal vessel plans and increase usage of bridges, as the widths of bridges and their opening regimes remain unchanged.

The following values are tested for the fleet size: 10, 25, 50 and 75 vessels. The rest of parameters take the following values: $\{\alpha, \beta\} = \{1, 1\}$, $H_p = 30$ minutes, normal traffic density profile and $N_{\text{up}}^{(i)}$ and $N_{\text{down}}^{(i)}$ are as in Table III. The corresponding values of the KPIs are summarized in Table IX. Larger fleet sizes lead to increased computation times, although the increase is not as sharp as it was for the prediction horizon. Passage operations at optimal values decreases with increased fleet sizes (first KPI), which makes sense since more vessels are competing for the same resources, and bridges must respect N_{up} and N_{down}. Bridge status switches increase (second KPI), which could be anticipated given that more vessels must pass the same bridges. Finally, there seems to be a general increasing trend in terms of bridge width utilization (third KPI), although this is not always the case.

4) Traffic density: In the context of this problem, traffic density describes the temporal distribution of optimal vessel passage times throughout the navigation period. This means that, as traffic density increases, more vessels within the considered fleet wish to pass bridges around the same time. Situations with higher traffic density are expected to decrease computation times, fulfillment of optimal vessel plans and bridge status switches, and increase bridge occupancy.

Three different traffic density profiles—normal, high, and very high—are tested. The rest of parameters take the following values: $\{\alpha, \beta\} = \{1, 1\}$, $H_p = 30$ minutes, $\mathcal{V} = 25$ and $N_{\text{up}}^{(i)}$ and $N_{\text{down}}^{(i)}$ are as in Table III. The corresponding values of the KPIs are summarized in Table X. Computation time decreases with traffic density as optimal vessel passage times are less scattered throughout the navigation period, hence the simulations conclude earlier. Increased traffic density decreases both the number of passage operations at optimal values (first KPI) and the number of bridge status switches (second KPI) decrease for increased traffic densities. The fact that more vessels wish to pass the same bridges closer in time means that the percentage of vessels that see their optimal passage times fulfilled decreases (given the bounded bridge

TABLE X
SENSITIVITY TO TRAFFIC DENSITY

		Computation time [s]	Vessel passage at $\tau_o^{(i,j)}$ [%]	Bridge status switches	{min., avg., max.} bridge width occupancy [%]
Traffic density	Normal	925.47	B1: 40 B2: 48 B3: 80	B1: 16 B2: 20 B3: 26	B1: {0.15, 0.37, 0.91} B2: {0.17, 0.45, 0.95} B3: {0.18, 0.42, 0.79}
	High	676.82	B1: 28 B2: 32 B3: 64	B1: 12 B2: 16 B3: 18	B1: {0.33, 0.53, 0.94} B2: {0.36, 0.55, 0.98} B3: {0.35, 0.56, 0.88}
	Very high	508.33	B1: 20 B2: 28 B3: 52	B1: 8 B2: 10 B3: 12	B1: {0.45, 0.57, 1} B2: {0.44, 0.54, 1} B3: {0.41, 0.60, 0.96}

TABLE XI
SENSITIVITY TO BRIDGE OPENING REGIMES

		Computation time [s]	Vessel passage at $\tau_o^{(i,j)}$ [%]	Bridge status switches	{min., avg., max.} bridge width occupancy [%]
Opening regimes	Normal	925.47	B1: 40 B2: 48 B3: 80	B1: 16 B2: 20 B3: 26	B1: {0.15, 0.37, 0.91} B2: {0.17, 0.45, 0.95} B3: {0.18, 0.42, 0.79}
	Permissive	671.99	B1: 68 B2: 80 B3: 92	B1: 20 B2: 28 B3: 28	B1: {0.11, 0.30, 0.67} B2: {0.05, 0.37, 0.99} B3: {0.17, 0.40, 0.78}

width capacity), and also that bridges need to open and close fewer times (although maximum up-times must be observed). Finally, bridge width occupancy increases for increased traffic density: when bridges are open, a larger number of vessels take advantage of this situation to pass.

5) Bridge opening regimes: Although bridge opening regimes are adaptable to navigation demand, they remain constrained by the maximum up-time and minimum down-time of the bridge. Then, the larger the former and the smaller the latter are, the more permissive a bridge opening regime is. Such a permissive regime is expected to lead to higher fulfillment of optimal vessel plans and bridge status switches, although its effect on computational time is hard to anticipate.

The following values are tested for the bridge opening regimes: the normal regime, characterized by $N_{up} = \{10, 10, 15\}$ minutes and $N_{down} = \{15, 10, 5\}$ minutes, and a more permissive opening regime, characterized by $N_{up} = \{15, 20, 25\}$ minutes and $N_{down} = \{10, 5, 5\}$ minutes. The rest of parameters take the following values: $\{\alpha, \beta\} = \{1, 1\}$, $Hp = 30$ minutes, and $\mathcal{V} = 25$. The corresponding values of the KPIs are summarized in Table XI. It can be noticed how the more permissive bridge opening regime incurs a lower computation time than the normal regime, which may be due to a possible lower number of constraints in the problem. Naturally, the relaxed bridge opening schedule allows for an increased number of decisions at optimal passage times (first KPI), as bridges are less constrained in their up- and down-times. Another consequence of the less restrictive down-times is that bridge status switches increase (second KPI), whereby bridges can open sooner after an open-close switch than in the normal regime. Finally, bridge width utilization decreases as the result of increased bridge status switches (third KPI).

VI. CONCLUSIONS AND FUTURE RESEARCH

This paper addresses the IWT problem in the presence of movable bridges, and proposes the dynamic coordination of bridge operations and vessel navigation using adaptable bridge opening regimes to exploit vessel passage demand. This operational problem is recast in the control framework, and a model predictive control strategy is designed to solve the problem. Qualitative information about vessel-bridge interactions is incorporated into the control problem in the form of linear constraints. Extensive testing of the solution is conducted in two steps. First, the results are compared to those obtained using the approach presented in [19], which was characterized by fixed bridge opening regimes. Percentage of vessels assigned to pass at their optimal passage time, number of bridge status switches, and minimum, average and maximum relative bridge width occupancy are used as KPIs to assess the performances of both solutions. A direct comparison of these values allows to demonstrate the superior performance of the adaptable strategy in terms of optimal vessel voyage plan satisfaction and reduced computational burden. Second, a sensitivity analysis is carried out to assess the effect of the numerical values of the main parameters of the adaptable approach—objective function weights, prediction horizon, fleet size and bridge opening regimes—on the final solution. The same KPIs are used, allowing to reach conclusions in terms of how to tune these parameters so that the desired performance can be attained.

This paper has demonstrated a proof of concept, showing that the proposed approach has the potential to be incorporated into real IWT management systems. It is worth noting that Rijkswaterstaat[2], the Dutch agency that is concerned with the management of roads and waterways, is already using a solution that exploits V2I and I2V communication, although their approach is closer to the fixed opening regime case. Therefore, the adaptable opening regime algorithm presented in this paper could be of interest to inland waterways authorities. This research constitutes a first step in this direction.

The proposed adaptable bridge opening regime approach should not only appeal IWT management organizations, but also individual vessel skippers, given the time savings this approach offers compared to the fixed opening regime case. However, it is good to note that, in addition to improved journey times, fuel consumption is also very relevant to vessel skippers. Fuel consumption savings should be quantified in future research activities to further justify the adequacy of the approach, although this probably requires to incorporate more detailed vessel models. In turn, the explicit consideration of fuel consumption would also allow to analyze the impact of the proposed approach on the environment.

The applicability of the proposed approach to real IWT management problems might be hindered by a number of factors, which requires to explore several research avenues on the basis of the results obtained. On the one hand, larger prediction horizons—and, to a lesser extent, fleet sizes—were shown to increase computation times drastically. It would then be interesting to explore distributed optimization approaches [48] to mitigate the computational burden. On a wider note, the approach can be further applied to consider locks with ship placement capabilities by adapting the approach presented in [44, Ch. 5], while also addressing the bidirectional traffic case in any possible waterway network topology.

[2]https://www.rijkswaterstaat.nl/en

Appendix A
Implementation details

The MPC implementation is shown in Algorithm 1. The information provided by vessels and bridges allows the coordinator to solve the MPC problem, thus determining vessel passage times, and bridge opening and closing periods.

Algorithm 1 Model predictive control implementation

Require: $b^{(i)}, N_{\text{up}}^{(i)}, N_{\text{down}}^{(i)}, v^{(j)}, \tau_e^{(i,j)}, \tau_o^{(i,j)}, \forall i \in \mathcal{B}, \forall j \in \mathcal{V}_k$
Ensure: $u_k^{(i,j)}, \ \forall i \in \mathcal{B}, \forall j \in \mathcal{V}_k, \forall k \in \mathcal{K}$

```
Set k = 1 and define x_1^(i) = 0, z_1^(1,j) = 1 and ω_1^(j) = 0, ∀i ∈ B, ∀j ∈ V_1
while m_k > 0 do
    Formulate and solve problem (19) for V_k
    Extract u_{k|k}^(i,j) from solution of problem (19) and determine x_{k+1}^(i,j), z_{k+1}^(i,j), ω_{k+1}^(j) and s_k^(i) using Eqs. (2), (6)–(15)
    for i ∈ B do
        for j ∈ V_k do
            if u_{k|k}^(i,j) = 0 then
                Vessel j has not been assigned a passage time through bridge i: keep in V_{k+1}^(i)
            else
                if ω_{k+1}^(j) = 0 then
                    Vessel j has been assigned a passage time through bridge i ≠ n: move to V_{k+1}^(i+1)
                else
                    Scheduling of vessel j is completed: do not add to V_{k+1}^(i), ∀i ∈ B
                end if
            end if
        end for
    end for
    k ← k + 1
end while
```

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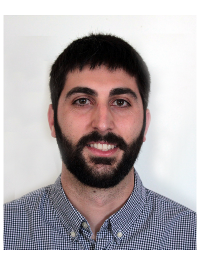

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