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Addressing water level uncertainty for inland waterway transportation: a partially joint chance-constrained programming approach

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1 Introduction

Intermodal freight transportation is regarded as a transportation strategy to enhance environmental sustainability and operational efficiency, seamlessly integrating various modes such as trucks, rail, ships, airplanes, and cargo bikes. Furthermore, authors in [1] have highlighted that intermodal transport, supported by the European Commission as well as by national and regional governments, is actively promoting a modal shift from road transport to inland waterways and railways. Consolidation-based carriers, including rail and navigation companies, play a crucial role in intermodal freight transportation by efficiently achieving economies of scale, optimizing service networks, and meeting diverse shipper requirements. Their primary objective is to maximize net profits while satisfying the needs and specifications of shippers, involving the establishment of a resource- and cost-efficient service network and schedule informed by forecasted demand.

Concentrating on specific aspects of the consolidation-based intermodal freight transportation problem, incorporating Inland Waterway Transportation (IWT), we first turn our attention to [2], where Tawfik and Limbourg examined this problem using a service network design model and a scenario-based analysis approach. For an in-depth exploration of tactical planning in intermodal freight transportation for IWT carriers, we refer to [3],

where Bilegan *et al.* addressed this aspect and proposed a new service network design model integrating both resource and revenue management considerations.

The significance of IWT, often underutilized in intermodal freight logistics, has been underscored in recent decades thanks to its cost-effectiveness, energy efficiency, and overall environmental sustainability. Nevertheless, the integration of inland waterways into the intermodal transport network presents both opportunities and challenges. This is primarily attributed to the rather difficult predictability of water levels, which can impact transit times and vessels capacities, potentially affecting the efficiency and reliability of IWT. In this context, our focus is on a critical aspect of IWT, namely the tactical planning problem for consolidation-based intermodal freight transportation carriers. We introduce novel considerations on this decision-making type of problems and, more broadly, on addressing uncertainty arising from water level variations within mathematical programming models. This work is advancing the studies initiated in [3], by explicitly introducing an important source of uncertainty that affects the tactical planning performed in IWT and impacts the design of the decision-making framework, models and solution techniques.

2 Uncertainties of water level and induced vessel capacity

Water level, a critical factor in IWT, undergoes significant fluctuations influenced by seasonal weather conditions. It plays a crucial role in determining the navigability of rivers and canals, directly impacting the cargo capacity of vessels operating in these waterways. However, as highlighted in [4], most of the existing research work focuses on uncertainties related to demand, transit time, and cost, with limited attention given to capacity, particularly in the context of capacity influenced by water levels. Insufficient water levels may compel vessels to reduce their carrying capacity to prevent grounding or hull damage, resulting in prolonged transit times and increased transportation costs. This situation might require the use of container trucks, incurring additional expenses to transport cargo beyond the vessel’s capacity in specific sections of the river or canal affected by low water levels. Conversely, excessive water levels may hinder vessels from passing under bridges or through locks, leading to delays and disruptions in supply chains. Consequently, variations in water levels directly impact the loading capacity of vessels within inland waterways.

3 Handling the uncertainty of water levels

We assume known a piece-wise linear function [5], denoted $g(l, i, j)$, establishing the relationship between the water level on the physical link (i, j) and the corresponding carrying capacity $cap(l, i, j)$ when sailing between terminals i and j for each vessel type l . Let us consider the general upper bound constraint on the capacity of a ship navigating in a specific river section, expressed as: $\sum_{d \in D} x(d, s, k) \leq cap(l(s), i_k, i_{k+1})y(s), \forall k \in K(s), s \in S$.

Here, the continuous decision variable $x(d, s, k)$ represents the volume of demand $d \in D$ transported by the leg $k \in K(s)$ of a service $s \in S$, the binary decision variable $y(s)$ takes the value of 1 if service s is activated, $l(s)$ specifies the vessel type used by a service s , i_k and i_{k+1} denote respectively the origin and destination terminals of leg k , and $\text{cap}(l(s), i_k, i_{k+1})$ indicates the transportation capacity of a service s on leg k .

When considering the practical settings of inland waterway transportation systems, one often finds that the fluctuations in water levels exhibit a non-uniform distribution along the river or canal. Rather than being evenly spread, these changes persist over extended distances and time, affecting specific sections and highlighting the uncertainty in water levels. Therefore, the modeling approaches relying on classical individual or joint chance constraints may prove either too lax or excessively restrictive when performing the tactical planning. These approaches might fail to properly formulate the desired feasibility guarantees for the tactical transportation plan, i.e., the planned freight itineraries being feasible on certain zones of the network that are viewed as strategic.

To address this limitation, we propose a partially joint chance-constrained variant that incorporates a designated partially joint partition set, denoted as Ω . This set comprises subsets of indexes corresponding to the capacity constraints that are used to define the probabilistic constraints. These subsets, denoted as Ω_ξ , enable the grouping of interconnected sections of the river or canal. Each such subset, individually constrained, maintains the associated probabilistic constraints jointly constrained within this subset. By employing this approach, one may appropriately consider and group together diverse geographical or infrastructure characteristics within different sections of the physical waterway network, thereby enhancing the overall modeling consistency. Moreover, from a managerial perspective, we suggest introducing a so-called tolerated volume Tol_{Ω_ξ} (i.e., an upper bound on available capacities of other non-IWT modes needed to handle the exceeding volumes of cargo not able to be transported by waterway) as a proactive measure to mitigate the adverse effects of fluctuating water levels within each subset Ω_ξ . This approach is designed to offer a flexible and adaptable solution for effective system management under varying conditions.

To numerically implement this approach, we introduce the continuous variable $\tilde{w}(s, k)$, which represents the required capacity adjustment that would be necessary to satisfy the probabilistic capacity constraint, when the activated service lacks sufficient capacity $\tilde{\text{cap}}(l(s), i_k, i_{k+1})$ to accommodate the demands on its k^{th} service leg due to the uncertain water level. By configuring the specific tolerated volume Tol_{Ω_ξ} for each subset Ω_ξ , we can effectively address the impact of fluctuating water levels and ensure the resilience of the system within a threshold of infeasibility, denoted by ϵ_{Ω_ξ} . A tolerance-based partially joint chance-constrained paradigm is then introduced to address the uncertainty of water

levels along the river or canal:

$$\sum_{d \in D} x(d, s, k) \leq \text{c}\tilde{\text{a}}\text{p}(l(s), i_k, i_{k+1})y(s) + \tilde{w}(s, k), \quad \forall s \in S, k \in K' \quad (1)$$

$$\mathcal{P} \left(\sum_{(s,k) \in \Omega_\xi} \tilde{w}(s, k) \leq \text{Tol}_{\Omega_\xi} \right) \geq 1 - \epsilon_{\Omega_\xi}, \quad \forall \Omega_\xi \in \Omega \quad (2)$$

$$\tilde{w}(s, k) \geq 0, \quad \forall s \in S, k \in K' \quad (3)$$

The aforementioned probabilistic constraints (1)-(3) present challenges in resolution, even when the probability distributions for water levels are formulated using classical random distributions. The present study tackles this issue by developing a MILP reformulation aligned with constraints (1)-(3). It incorporates a finite set of water level scenarios across a relevant inland waterway physical network and time horizon, along with an efficient approach to solve the large-scale instances.

In this study, we aim to tackle water level uncertainties within consolidation-based intermodal freight transportation, focusing on inland waterway networks. The MILP reformulation, incorporating constraints (1)-(3) in accordance with the partially joint chance-constrained paradigm and the concise representation of the investigated problem will be presented during the Odysseus conference, as well as elements of the experimental setting used, numerical results and analyses performed.

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