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Constraint satisfaction problem based on flow graph to study the resilience of inland navigation networks in a climate change context ⋆

H. Nouasse * **A. Doniec** * **G. Lozenguez** * **E. Duviella** * **P. Chiron** **
B. Archimède ** **K. Chuquet** ***

* *Mines Douai, IA, F-59508 Douai, France - Université de Lille, France*
(corr. author: houda.nouasse@mines-douai.fr).
** *ENIT-LGP, Tarbes, France*
*** *Voies Navigable de France, Service de la navigation du Nord, Lille, France*

Abstract: The T-Ten European program aims at optimizing the transport logistics in Europe by promoting alternative transport modes. Navigation transport offers a competitive and environmentally friendly alternative. Hence, it is foresaw an increase of the navigation transport demand that it will be necessary to accommodate. This will be very challenging particularly in a global change context where less available water resource is expected. A constraint satisfaction problem based on flow graph is proposed in this paper to study the resilience of inland navigation networks against increase of the navigation demand and extreme events. Drought and flood scenarios are simulated considering an network composed of five interconnected navigation reaches. The results show that the designed tools are well adapted to the resilience study of inland navigation networks.

Keywords: Resilience, Constraint satisfaction problems, Graphs, Navigation networks, Water management, Global change.

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1. INTRODUCTION

Inland navigation transport is part of the multimodal transport that is promoted by the Trans-European network program (TEN-T [1]). This program aims at developing new transport infrastructure policy to close the gaps between Member States' transport networks and to guaranty seamless transport chains for passenger and freight. To well integrating the inland navigation transport in this framework, an efficient water management strategy is required. It consists in guaranteeing the navigation conditions even if an increase of navigation demand and extreme events due to climate change is expected Bates et al. (2008). The intergovernmental panels as the IPCC (*Intergovernmental Panel on Climate Change*) has defined RCP scenarios (*Representative Concentration Pathways*) on which future forecasts on temperature and rain can be generated IPCC (2014). Based on these scenarios, the flood and drought events will be more frequent and mode intensive in close future Boé et al. (2009); Ducharne et al. (2010); Wanders and Wada (2015); Li et al. (2015); Park et al. (2015). Thus, constraints on water resource management for navigation will be bigger.

To deal with the navigation demand increase and the climate change effects, adaptive water management strategies have to be designed. An adaptive and predictive control architecture was proposed in Duviella et al. (2013). It is based on the multiscale modeling approach proposed in Duviella et al. (2014) to reproduce the dynamics of inland navigation networks during flood and drought events. This architecture is improved in this paper to consider events that can impact large areas on larger periods. It consists in dispatching volumes of water through the network to guarantee enough water in each part of the network. Thus, the designed tools aim at determining the resilience of the inland navigation networks. They are based on an integrated model of inland navigation network that allows locating the navigation reaches, the locks and gates and identifying the main water intakes. Then a flow graph is proposed to determine the possible paths between the navigation reaches and the main constraints on water volume exchanges. Network flow problems have been widely used for the computation of maximum flow or minimum cost flow in several areas such as transportation Silver and de Weck (2007), telecommunication Fekete et al. (2008), job scheduling or flood attenuation Nouasse et al. (2013). Finally, a constraint satisfaction problem is defined to determine the water volumes that have to be exchanged between each navigation reach. Mathematical programming in general Passchyn et al. (2016) and constraint satisfaction in particular Sun et al. (2014) is a major tool to address the problems of transport.

The management objectives of waterways are given in Section 2. Section 3 allows formulating the problem of this management during drought and flood periods. The integrated model is detailed. Then, the constraint satisfaction problem is proposed. All the designed tools allows considering inland navigation networks that are composed of several confluents and diffluents. In Section 4, an academical example of inland navigation networks composed of five interconnected navigation reaches is considered. Its characteristics have been determined

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[1] `http://ec.europa.eu/transport/themes/infrastructure/ten-t-guidelines/index_en.htm`

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considering real navigation networks. This case study allows detailling the design step of the proposed tools. Finally, drought and flood events are simulated to highlight the performances of the designed tools.

2. WATERWAYS MANAGEMENT

Waterways are equipped and opened to passenger transport, cargo and boating. Their different uses have an economic benefit Mihic et al. (2011); Mallidis et al. (2012); Brand et al. (2012). It is observed that inland navigation network is constituted by a number of hydraulic structures, including locks. A part of an inland navigation network between two locks is defined as a Navigation Reach (NR). It is assumed that in general navigation requirements are the same for each NR. Navigation is maintained in a reach respecting the so called navigation rectangle. The boundaries of the navigation rectangle are the High Navigation Level (HNL) and the Low Navigation Level (LNL). The main management objective consists in keeping the water level in each NR is inside the navigation rectangle and close to the Normal Navigation Level (NNL). The waterways have to be supplied with natural rivers. Climate change impacts severely on the availability of water resources, more accurately during floods and drought. Flood periods are as problematic as droughts. For example, in extreme climate scenarios natural water reserves may reach their ecological limits in the absence of management of excess volumes of water. This case represents a deficit situation in water resources during drought. Thus, the resilience study of inland navigation networks is necessary. We can assume that the resilience study is an approach based on the fact to propose a set or rather a system of rules for maintaining "the proper" functioning or sometimes simply the functioning of an inland navigation network. The main objective would be to adapt to extreme conditions such as floods or drought. The needs of each of these situations are unlike those of the other that is why we need to establish a stable and adaptive resilience "system" (as we suppose that is a system of rules). Stable in the sense to resist change and adaptive in the sense of accompanying that change. When one fails to offer a solution, the system does not fail but reveals its limits (it can also be considered a form of adaptation). An understanding of the functioning and needs of each component of the network, in particular NR, is an important step in determining strategies that will be adapted on a microscopic level to each of them and on a macroscopic point of view to their interaction with the entire network and climate change. To address this issue, authors in Duviella et al. (2013) proposed an adaptive and predictive control architecture.

3. PROBLEM MODELING

3.1 Inland navigation reach model

The integrated model is proposed to model several configurations of inland navigation networks by considering two elementary configurations: a confluence and a diffluence (*see* Figure 1.a). Networks are composed with a finite number η of interconnected NR. NR are numbered and denoted NR_i, with $i \in 1$ to η. The NR_i is modeled as a tank that contains a volume of water, denoted $V_i(t)$. According to the boundaries of the navigation rectangle, to the NNL and to the geometrical characteristics of each NR_i, it is possible to determine the volumes that corresponds to the NNL, the HNL and the LNL such as $V_i^{LNL} \leq V_i^{NNL} \leq V_i^{HNL}$. The management objective is $V_i(t) = V_i^{NNL}$ and at least $V_i^{LNL} \leq V_i(t) \leq V_i^{HNL}$. If this condition is broken, the navigation has to stop.

A NR_i is supplied and is emptied by controlled and uncontrolled water volumes (*see* Figure 1.b). Controlled water volumes gather the water that is coming from controlled gates and from the lock operations. Uncontrolled water volumes are all the withdrawals and supplies from water intakes located along the NR_i. It is also possible to consider the water exchanges with groundwater.

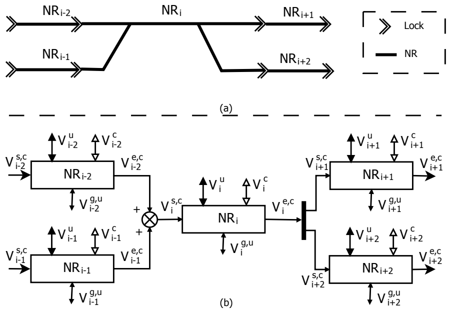

Fig. 1. (a) Inland navigation network, (b) its integrated model.

Thus, the set of controlled water volumes is composed of:

- controlled volumes from the upstream NR that supply the NR_i, denoted $V_i^{s,c}$ (s: supply, c: controlled),
- controlled volumes from the NR_i that empty the NR_i, denoted $V_i^{e,c}$ (e: empty),
- controlled volumes from water intakes that can supply or empty the NR_i, denoted V_i^c. These volumes are signed; positive if the NR_i is supplied, negative otherwise.

The set of uncontrolled water volumes is composed of:

- uncontrolled volumes from natural rivers, rainfall-runoff, Human uses, denoted V_i^u (u: uncontrolled). These volumes are signed depending of their contribution to the volume $V_i(t)$ in the NR_i.
- uncontrolled volumes from exchanges with groundwater, denoted $V_i^{g,u}$ (g: groundwater). These volumes are also signed.

Based on the definition of the water volumes that contribute to the volume contained in the NR_i, it is possible to model its dynamics by:

$$V_i(t) = V_i(t-1) + V_i^{s,c}(t) - V_i^{e,c}(t) + V_i^c(t) + V_i^u(t) + V_i^{g,u}(t). \quad (1)$$

The dynamics of the NR_i have to take into account the configuration of the network. For a confluence, the controlled volumes coming from all the NR that are located upstream the NR_i are added. For a diffluence, the controlled volumes that empty the NR_i correspond to the sum of the controlled volumes that supply the downstream NR (*see* relation (2)).

$$\begin{cases} V_i^{s,c}(t) = \sum_{j \in \Omega_i} V_j^{e,c}(t), \\ V_i^{e,c}(t) = \sum_{j \in \Theta_i} V_j^{s,c}(t), \end{cases} \quad (2)$$