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To cite this version:
Houda Nouasse, Arnaud Doniec, Guillaume Lozenguez, Eric Duviella, Pascale Chiron, et al.. Constraint satisfaction problem based on flow graph to study the resilience of inland navigation networks in a climate change context. 8th IFAC Conference on Manufacturing Modelling, Management and Control (MIM 2016), Jun 2016, Troyes, France. pp. 331-336, 10.1016/j.ifacol.2016.07.626. hal-01490602

HAL Id: hal-01490602
https://hal.archives-ouvertes.fr/hal-01490602
Submitted on 15 Mar 2017

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To cite this version:

Nouasse, Houda and Doniec, Arnaud and Lozenguez, Guillaume and Duviella, Eric and Chiron, Pascale and Archimède, Bernard and Chuquet, Karine Constraint satisfaction problem based on flow graph to study the resilience of inland navigation networks in a climate change context. (2016) In: 8th IFAC Conference on Manufacturing Modelling, Management and Control (MIM 2016), 28 June 2016 - 30 June 2016 (Troyes, France).
Constraint satisfaction problem based on flow graph to study the resilience of inland navigation networks in a climate change context

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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.

1. INTRODUCTION

Inland navigation transport is part of the multimodal transport that is promoted by the Trans-European network program (TEN-T1). 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); Ducharme 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 multi-scale 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 confluentes and diffuents. In Section 4, an academical example of inland navigation networks composed of five interconnected navigation reaches is considered. Its characteristics have been determined.
considering real navigation networks. This case study allows
detailing 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 bene-
fit 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 repre-
sents 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 objec-
tive 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 configu-
trations of inland navigation networks by considering two el-
cementary configurations: a confluence and a diffluence (see
Figure 1a). Networks are composed with a finite number \( \eta \) of
interconnected NR. NR are numbered and denoted \( N_{R_i} \), with
\( i \in 1 \) to \( \eta \). The \( N_{R_i} \) 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 \( N_{R_i} \), 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 \( V(t) = V_{NNL} \), 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 uncon-
trolled water volumes (see Figure 1b). Controlled water vol-
umes 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.](image)

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

- controlled volumes from the upstream \( NR_i \) 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
either 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 vol-
  umes 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:

\[
V_i(t) = V_i(t-1) + V_{i,e,c}(t) - V_{i,e,c}(t) + V_{i,c}(t) + V_{i,s,c}(t) + V_{i,g,u}(t).
\]

The dynamics of the \( NR_i \) have to take into account the configu-
ration 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)).

\[
\left\{
\begin{array}{l}
V_{i,e,c}(t) = \sum_{j \in D_i} V_{j,e,c}(t), \\
V_{i,c}(t) = \sum_{j \in T_i} V_{j,c}(t),
\end{array}
\right.
\]
where $\Omega_{i}$ gathers all the index of the NR that supply the $NR_{i}$, and $\Theta_{i}$ all the index of the NR that are supplied by the $NR_{i}$.

The proposed integrated model requires the knowledge of all the possible water volume contributions. It is necessary to identify all the controlled volumes and to estimate all the uncontrolled volumes. This knowledge comes from the waterways managers.

In this paper, we propose to set some assumptions. Water exchanges with groundwater are nonexistent. The controlled water volumes $V_{i}^{c}$ from water intakes are bounded with the known minimal and maximal daily volumes of water. The water volume that corresponds to each lock operation is known. Finally, the daily average number of ships that cross the inland navigation network is known.

### 3.2 Flow-based network modeling

We choose in the following to model inland navigation network as a graph. The answers related to questions about the specific requirements for operating a navigation system are made by considering a flow problem on this graph. The volume management in such a network is guaranteed by satisfying the constraints formulated for this problem.

Let consider a network, $G = (G_{x}, G_{a})$, defined as a connected Directed Acyclic Graph (DAG), where $G_{x}$ is the set of nodes and $G_{a}$ is the set of arcs. The set of nodes $G_{x}$ contains the nodes representing each reach in the navigation network $NR_{i}$ and two additional nodes, $O$ and $N$, respectively source and sink. We denote each directed arc $a = (NR_{i}, NR_{j})$ with nodes corresponding to navigation reaches, such as $NR_{i}$ is the leaving node (the tail of arc $a$) and $NR_{j}$ is the entering node (the head of arc $a$). To simplify notations, we will consider that nodes are labeled with the index of each $NR_{i}$, i.e., $a = (NR_{i}, NR_{j}) = (i, j)$ or $a = (O, NR_{j}) = (O, j)$. As mentioned in (3.1), the link between two adjacent reaches $NR_{i}$ represents a water volume amount. Thus, we consider an s-t flow routing (source-to-sink flow) in the network described by the water volume path between different reaches. Figure 2 shows an example of a flow network model by considering the navigation network proposed in Figure 1. The arcs are directed according to the configuration of the navigation network. According to the proposed assumptions, the node $O$ gathers all the volumes of water that supply the navigation network from natural rivers. The node $N$ gathers all the volumes of water from the navigation network. On every arc in $G_{a}$, it is defined a flow variable $\phi_{a}, a \in G_{a}$ that can be expressed by $\phi_{a,j}$. This flow varies with respect to capacities constraints and demands relation on each node.

One step in the management of water volumes in the inland navigation network is, for example, if one refers to this network $G$, to determine the flow that guarantees different navigation scenarios for a given period of time. That can be formulated as follows:

\[
\text{Maximize } \phi \\
\text{subject to } \begin{cases} l_{a} \leq \phi_{a} \leq u_{a} & \text{for } a \in G_{a} \\ \Phi \geq 0 \end{cases}
\]

by considering these additional constraints

\[
\phi_{a+} - \phi_{a} = d(i) \text{ for } i \in G_{x} - \{O, N\},
\]

This constraints allows flow on a given node $i$, not to be conservative. In order to respect the navigation conditions on each reach $NR_{i}$, the demand of water volumes on each node representing a $NR_{i}$ is defined as:

\[
d(i) = V_{i}^{NNL} - V_{i}(t), \quad i \in G_{x} - \{O, N\}
\]

that must verify the following relation:

\[
V_{i}^{NNL} - V_{i}^{HNL} \leq d(i) \leq V_{i}^{NQL} - V_{i}^{QL} \quad i \in G_{x} - \{O, N\}
\]

where $\Phi$ is a vector that contains all the flow $\phi_{a}, l_{a}$ and $u_{a}$ the lower and upper bound capacities of the arc $a$, $a^{+}$ the arcs leaving the node $i$ and $a^{-}$ the arcs entering the node $i$, and $d(i)$ the demand of the node $i$. We also assume that $\phi_{a}(O) = d(O)$ and $\phi_{a}^{-}(N) = -d(O)$ as $d(O)$ is the known supply on the source node.

The design of the integrated model (see Figure 1.b) helps to build the flow network and to determine the capacities that are expressed in volume. The lower and upper bound capacities of the arc $a$, i.e. $l_{a}$ and $u_{a}$, depend on the configuration and equipment of the inland navigation networks. Hence, we define $\Psi$ the set of the index of the upstream $NR_{i}$ that are not supplied by another $NR_{i}$, and $\Xi$ the set of the index of the downstream $NR_{i}$ that not supply another $NR_{i}$. By considering example in Figures 1 and 2, these sets are $\Psi = \{i - 2, i - 1\}$, and $\Xi = \{i + 1, i + 2\}$. Thus:

- upper bound capacities for arcs between two $NR_{i}$, i.e. $\{i - 2, i\}, \{i - 1, i\}, \{i, i + 1\}$, $\{i, i + 2\}$ in Figure 2, are computed as the sum of the maximum available controlled water volumes ($V_{i}^{c}$),
- lower bound capacities for arcs between two $NR_{i}$, are only the required water volumes for the navigation ($V_{i}^{r,c}$)
- upper bound capacities for arcs between $O$ and $NR_{j}$, $j \in \Psi$, i.e. $\{O, i - 2\}, \{O, i - 1\}$, are computed as the sum of the maximum available controlled water volumes ($V_{i}^{C,c}$), the maximum available water volumes from water intakes (maximum positive $V_{i}^{c}$) and the positive uncontrolled water volumes ($V_{i}^{u}$),
- lower bound capacities for arcs between $O$ and $NR_{j}$, $j \in \Psi$, are the sum of the required water volumes for the navigation ($V_{i}^{C,c}$) and the positive uncontrolled water volumes ($V_{i}^{u}$),
- upper bound capacities for arcs between $O$ and $NR_{j}$, $j \not\in \Psi$, i.e. $\{O, i\}, \{O, i + 1\}, \{O, i + 2\}$, correspond to the sum of the maximum available water volumes from...
water intakes (maximum positive $V_i^+$) and the positive uncontrolled water volumes ($V_{i}^U$),

- lower bound capacities for arcs between $O$ and $NR_j$, $j \not\in \Xi$, are only the positive uncontrolled water volumes ($V_{i}^U$),

- upper bound capacities for arcs between $NR_j$, $j \not\in \Xi$, and $N$, i.e. $\{(i-2, N), (i-1, N), (i, N)\}$, correspond to the sum of the maximum available controlled water volumes ($V_{i}^{c,c}$), the maximum water volumes that can empty the $NR$ (minimum negative $V_i^-$) and the negative uncontrolled water volumes ($V_{i}^U$),

- lower bound capacities for arcs between $NR_j$, $j \not\in \Xi$, and $N$, are only the negative uncontrolled water volumes ($V_{i}^U$),

- upper bound capacities for arcs between $N$ and the $NR_j$, $l \in \Xi$, i.e. $\{(i+1, N), (i+2, N)\}$, are the sum of the maximum available controlled water volumes ($V_{i}^{c,c}$), the maximum water volumes that can empty the $NR$ (minimum negative $V_i^-$) and the negative uncontrolled water volumes ($V_{i}^U$),

- lower bound capacities for arcs between $N$ and the $NR_j$, $l \in \Xi$, are the sum of the required water volumes for the navigation ($V_{i}^{c,o}$) and the negative uncontrolled water volumes ($V_{i}^U$).

### 3.3 CSP & Relaxation

In the following, we propose a CSP approach to determine the resilience of our system in the flow network $G$. Indeed, by definition CSP allows to evaluate in a finite domain a number of possible solutions. Unlike classical methods of solving a flow problem where the solution consists of finding a s-t flow augmenting path, CSP solving is based on search algorithms that aim on domain exploration for values of consistent variables. For example one may want to “augment” the water volume between two reaches but in that case we can not maximize flow between these two reaches so the arc connecting them is excluded from the optimal path. While in a CSP perspective, we will try to “best” satisfy this constraint of water volume required between the two reaches and if it is not satisfied it will be considered as an event to address in our resilience study. Hence, the approach we consider, for volume management in the navigation network, is to first solve a constraint satisfaction problem that can check as a priority that the level of water in the reaches is as close as possible to the NNL, and releases and river inputs are near zero. Such a problem is over-constrained and given the conflictual aspect of the problem: in order to maintain the water level around the NNL between two reaches while one may be a reach water lack while the other is in surplus of water; we then need to consider more flexible constraints such tolerating releases and river inputs. Which generally comes back to consider a Max-CSP problem Dechter (2003) when it comes to satisfy a maximum number of constraints. Starting from an over-constrained problem we relax to ensure the satisfaction of new and more permissive constraints. In this formulation as variables, we have:

- $\phi_a$, flow variable on each arc $a \in G$, the domain $D(\phi_a)$ of $\phi_a$ expressed as a discrete interval whose bounds are calculated according to the number of ships $b$.

- $d(i)$ demand variable for every reach $i$ in the network. The domain $D(d(i))$ is set according to navigation conditions (see 3.2).

In addition to flow conservation constraint on each node, we consider that the two following constraints are possible:

$$|\phi_a - \min(D(\phi_a))| = 0,$$

when $a \in \{(i-2, N), (i-1, N), (i, N)\}$ and $a \in \{(O, i), (O, i+1), (O, i+2)\}$. With $\min(D)$ and $\max(D)$ respectively the minimal and maximal values of variables domain. This constraint helps reduce the relative contributions to releases or external resources compared to the ensembles of contributions.

$$|d(i) - V_i^{NNL}| = 0, \ i \in G_x - \{O, N\}$$

This constraint helps to keep water volume on each reach around NNL. We consider a relaxation of the problem in order to enlarge the set of solutions. For this, during the resolution, the constraints above (8) and (9) will be relaxed one after the other which comes in some way to progressively identify the responsible arcs of problem infeasibility.

$$\left|\sum_a \phi_a - \sum_a \max(D(\phi_a))\right| = 0,$$

when $a \in \{(i-2, N), (i-1, N), (i, N)\}$ and $a \in \{(O, i), (O, i+1), (O, i+2)\}$

$$\sum_i d(i) - z = 0, \ i \in G_x - \{O, N\}$$

such as,

$$\sum_i \min(D(d(i))) \leq z \leq \sum_i \max(D(d(i))),$$

The following algorithm show how constraint programming is integrated to calculate the maximum flow.

### 4. SIMULATION RESULTS

We apply our method on a network model composed of five reaches respecting the configuration described in Figure 3.a. This configuration is characterized by the presence of a junction reach. Each reach is supplied with a daily volume $V_i^{c,c}$. For example, $NR_1$ is supplied by operations of the lock $L_1$ with a
not being distributed in a uniform basis, so that each part of the surplus. Resources and water requirements in the network are undersupply because the demand for water is reached and when the volume of water in reaches is solicited. In this case, we notice that, at the contrary of the drought case, upstream reaches (NR1 and NR2) are both in surplus, NR3 as a junction reach, it is rather on surplus or undersupply which is the case of the downstream reach NR4.

Water volume changes in reaches are apparent even for one ship navigating in the network in the case of flood percentage of 200% (See Figure 5(b) left). The difference is substantial compared to a 100% increase when the reaches were filled of water or emptied as from a number of ships equal to 28 in the network (See Figure 5(a) left). On the other hand, the maximum number of ships allowed to navigate in the case 100% percentage of flood is 43 whereas it is 45 in the case of 200%. This means that the way in which the volume of water is distributed in the network, depending on the interactions studied in the network. Figure 5(a) describes the distribution of water volumes in the network when a flood estimated at an increase of 100% of water resources is indicated. The second scenario (see Figure 5(b)) represents an increase of about 200% of water resources. In this case, we notice that, at the contrary of the drought case, upstream reaches (NR1 and NR2) are both in surplus, NR3 as a junction reach, it is rather on surplus or undersupply which is the case of the downstream reach NR4.

The impact of drought manifests itself in the network, so that, from a number of ships; downstream reaches (NR3 and NR4) are undersupply because the demand for water consumption becomes important (values in red (see Figure 4)) in this case study one of the upstream reaches (NR2) is in surplus. Resources and water requirements in the network are not being distributed in a uniform basis, so that each part of the network respond to this lack of water differently. In addition to this navigation limitations are to expect in this network in a drought case, i.e., navigation can not be tolerated for a number of ships greater than 36/day when a decrease of 25% of water resources is indicated and not to a number greater than 28/day when there is a decrease of 75%. Downstream reaches emptied as soon as we have 9 ships that circulate in the network when the percentage of drought is 75% and 21 ships when there is a percentage of 25%. In the Figure 5, two flood scenarios are presented in Figures 4 and 5, refer respectively to scenarios of drought and flood. We assumed that the number of ships navigating in the network is known a priori, denoted b, with \( b = b_j \) for \( j = 1, \ldots, 5 \). In each of these situations, we represent the network state when the maximum number of ships is reached and when the volume of water in reaches is solicited.

Figure 3. (a) Inland navigation network composed of 5 NRs, (b) its integrated model.

Figure 4. (a) Drought 25% left \( b = 21 \) and right \( b = 36 \), (b) Drought 50% left \( b = 18 \) and right \( b = 32 \), (c) Drought 75% left \( b = 9 \) and right \( b = 28 \).
between the reaches, is important in determining the maximum capacity of the network in terms of navigation.

![Diagram](image)

**Fig. 5.** (a) Flood 100% left $b = 28$ and right $b = 43$, (b) Flood 200% left $b = 1$ and right $b = 45$

5. CONCLUSION

In this paper, a constraint satisfaction problem based on flow transport graph is proposed to determine the resilience of inland navigation networks against increase of the navigation demand and extreme events as drought and flood periods. The proposed tools are based on an integrated model of inland navigation networks. The constraint satisfaction problem allows determining the optimal management of water volumes during extreme events. The main objective is to keep the navigation conditions on each section of the navigation networks. If the navigation conditions are guaranteed, navigation transport could take part of the multimodal transport as a competitive transport mode. The proposed tools are tested using a network composed of five interconnected navigation reaches. The results show the efficiency of the method to evaluate the ability of the network to satisfy navigation conditions in the case of extreme climatic events. In future works, uncertainty on navigation demand and on available water resource will be considered.

REFERENCES

Bates, B., Kandziewicz, Z., Wu, S., and Palutikof, J. (2008). Climate change and water. Technical report, Intergovernmental Panel on Climate Change.

Boé, J., Terray, L., Martin, E., and Habets, F. (2009). Projected changes in components of the hydrological cycle in french river basins during the 21st century. *Water Resources Research*, 45.

Brand, C., Tran, M., and Anable, J. (2012). The uk transport carbon model: An integrated life cycle approach to explore low carbon futures. *Energy Policy*, 41, 107–124.

Dechter, R. (2003). *Constraint processing*. Morgan Kaufmann.

Ducharme, A., Habets, F., Pagé, C., Sauquet, E., Viennot, P., Déqué, M., Gascoin, S., Hachour, A., Martin, E., Oudin, L., Terray, L., and Thiéry, D. (2010). Climate change impacts on water resources and hydrological extremes in northern france. In *XVIII Conference on Computational Methods in Water Resources*. Barcelona, Spain.

Duvieilla, E., Horváth, K., Rajaoroisa, L., and Chuquet, K. (2014). Multi-scale modeling approaches of inland navigation networks for their management in a global change context. In *Transport Research Arena*. Paris La Défense, France.

Duvieilla, E., Rajaoroisa, L., Blesa, J., and Chuquet, K. (2013). Adaptive and predictive control architecture of inland navigation networks in a global change context: application to the cuinchy-fontinettes reach. In *IFAC conference on manufacturing modelling, management, and control*. Saint Petersburg.

Fekete, S., Hall, A., Köhler, E., and Kröller, A. (2008). The maximum energy-constrained dynamic flow problem. In J. Gudmundsson (ed.), *Algorithm Theory-SWAT 2008. Lecture Notes in Computer Science*, volume 5124, 114–126. Springer Berlin Heidelberg.

IPCC (2014). Climate change 2014. Technical report, The Core Writing Team, R. K. Pachauri and L. Meyer, Synthesis Report. URL https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf.

Jussien, N., Rochart, G., and Lorca, X. (2008). Choco: an open source java constraint programming library. In *CPAIOR08 Workshop on Open-Source Software for Integer and Constraint Programming (OSSICP08).*

Li, Y., Huang, H., Ju, H., Lin, E., Xiong, W., Han, X., Wang, H., Peng, Z., Wang, Y., Xu, J., Cao, Y., and Hu, W. (2015). Assessing vulnerability and adaptive capacity to potential drought for winter-wheat under the rcp 8.5 scenario in the huang-huai-hai plain. *Agriculture, Ecosystems & Environment.*

Mallidis, I., Dekker, R., and Vlachos, D. (2012). The impact of greening on supply chain design and cost: a case for a developing region. *Journal of Transport Geography*, 22, 118–128.

Mihic, S., Gulosin, M., and Mihajlovic, M. (2011). Policy and promotion of sustainable inland waterway transport in europe - danube river. *Renewable and Sustainable Energy Reviews*, 15(4), 1801–1809.

Nouasse, H., Chiron, P., and Archimède, B. (2013). A flood lamination strategy based on transportation network with time delay. *Water Science Technology Water Supply*, 68(8), 1668–1696.

Park, C.K., Byun, H.R., Deo, R., and Lee, B.R. (2015). Drought prediction till 2100 under {RCP} 8.5 climate change scenarios for korea. *Journal of Hydrology*, 526, 221–230.

Passchyn, W., Briskorn, D., and Spiekman, F.C. (2016). Mathematical programming models for lock scheduling with an emission objective. *European Journal of Operational Research*, 248(3), 802–814.

Silver, M. and de Weck, O. (2007). Time-expanded decision networks: A framework for designing evolvable complex systems. *Systems Engineering*, 10(2), 167–188.

Sun, C.C., Puig, V., and Cembrano, G. (2014). Combining csp and mpc for the operational control of water networks: Application to the richmond case study. In *19th IFAC World Congress*, 6246–6251. Cape Town, South Africa.

Wanders, N. and Wada, Y. (2015). Human and climate impacts on the 21st century hydrological drought. *Journal of Hydrology*, 526, 208–220.