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Simulation Study to Assess the Effect of Ship Beam on the Navigable Flow Conditions in Paris

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ABSTRACT: Traversing the river Seine in Paris is challenging for inland vessels due to the density and diversity of local traffic that is encountered in a confined environment. The waterway authority, Voies navigables de France (VNF), commissioned a study to assess the relevance of the current regulations when vessels of varying types cross Paris. A first simulation study showed that regulations based on length only may be too restrictive for ships with smaller beams [1]. This paper presents additional simulations executed on a full mission bridge simulator with ships of reduced beam. The main bottlenecks happen at different locations depending on the ship's beam and ships with smaller beam can sail at higher water levels than the ships considered in the first study. The maximum water levels for which safe passage is possible were determined for each ship. Finally, recommendations have been formulated, which were then discussed with VNF and stakeholders.

1 INTRODUCTION

The river Seine is a major axis of the French inland waterway transport network with a high traffic density. Traversing the city of Paris is challenging for inland vessels due to the variety of manoeuvres involved. In the city centre, the main artery of the waterway is passing in between two isles (south of the Ile Saint-Louis and north of the Ile de la Cité), so that larger ships have to deal with sharp bends in between these two islands. On top of that, there is a high number of historically important bridges where traffic has to pass underneath narrow arches while taking into account delicate current conditions on a bending trajectory (see Figure 1).

Currently, regulations [2] concerning the maximum ship length as a function of the water level of the river are put in place to ensure the safety of navigation. However, with increasing capacity demand and with new types of ships, the question arose whether the regulations are still up to date and whether the safety is sufficient to increase traffic and ensure the competitiveness of inland waterways transportation.

PIANC [3] published a three methods approach with the vision of optimizing inland waterways dimensions based on local constraints and on the present and future fleet plying the waterway. A first step in the design or upgrade of an existing waterway is to use national guidelines. If no national guidelines are applicable, the PIANC guidelines provide recommendations for the dimensions of fairways (Concept Design) that depend on a so-called safety and ease level, which is stipulated by the waterway authority.

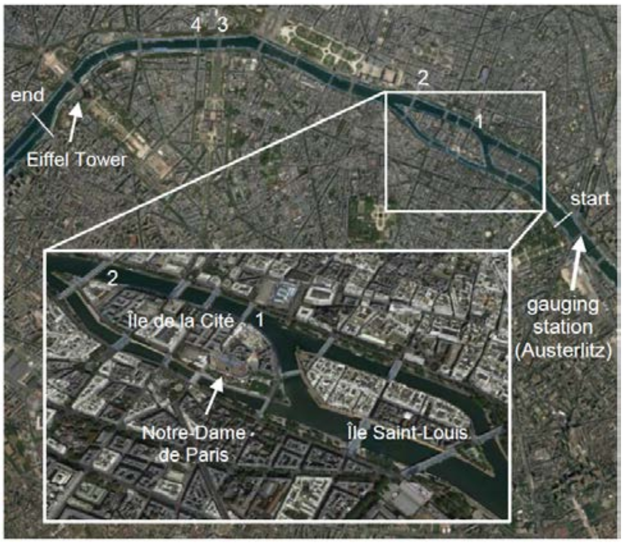

Figure 1. Study area: river Seine crossing the city of Paris, France. This paper focuses on the itinerary delimited by the start/end lines. The bridges Pont d'Arcole, Pont Neuf, Pont Alexandre III and Pont des Invalides are numbered from 1 to 4 respectively.

The Concept Design method has some limitations, e.g., it is not applicable in rivers with high flow velocities. Existing examples can then be used as a reference if the situation is comparable to the one studied (Practice Approach). When the situation is too different and large uncertainties remain or if environmental, local constraints limit the dimensions of the waterway, a third method (Detailed Design) is recommended.

Under bridges, PIANC recommends guaranteeing a minimum height on the total width of the fairway with an additional safety distance to account for collision risk. However, most of the waterways in France were designed before any regulations regarding air draft had been put in place [4] and the fleet has significantly changed over the last decades. In Paris, the minimum height under arch bridges would only be guaranteed over a very narrow width. Moreover, no guidelines are given for rivers with significant flow velocities. Therefore, the Detailed Design method was used in the present study using a ship manoeuvring simulator to reproduce the passage under bridges in specific hydro-meteorological conditions.

A comprehensive study assessing the maximum length of ships able to cross Paris under different hydraulic conditions has been conducted by the authors [1]. The study concentrated on the influence of length and ship type for 11.4 m wide ships sailing under narrow bridges and in sharp bends encountered on a stretch of 12 km of the river Seine crossing Paris and resulted in recommendations that were presented to VNF and stakeholders. However, the study showed that regulations based on ship length only are too restrictive for the actual fleet which consists of ships with smaller beams. This prompted VNF to commission a follow-up study in order to investigate how the recommendations would evolve when ships with smaller beams are also taken into account.

This paper describes the use of simulations to assess the operational limits with ships of reduced beam (closer to the present fleet characteristics) to complete the findings provided in the previous phase of the study [1]. Section 2 describes the simulation setup. Section 3 briefly presents the methodology applied to assess the safety of the manoeuvres and the main findings and challenges. A synthesis of the accessibility level based on length and beam is provided in Section 4. In Section 5, conclusions are given.

2 SIMULATION SETUP

2.1 *Manoeuvring simulators*

The full mission manoeuvring simulators at Flanders Hydraulics are dedicated for research studies and training. The main simulator is composed of a bridge with 360° aerial view of the surroundings projected on a cylindrical screen as shown on Figure 2. The bridge of all simulators is equipped with:

- ECDIS and radar;
- Controllable camera views;
- Controllable wheelhouse height;
- Propulsion and steering controls adapted to each ship type.

Figure 2. Main full mission bridge simulator with 360° view at FH.

2.2 *Waterway environment*

A total length of 12 km of the river Seine crossing Paris was modelled in 3D. The 3D environment was divided into two independently designed parts:

- 3D external view : this was the visible part of the environment above the waterline (see Figure 3). This part was projected on screens and allowed the skipper to orient himself. The visual aspect of the external environment created was of medium resolution except for bridges which were accurately reproduced (+/- 10 cm) from original plans.

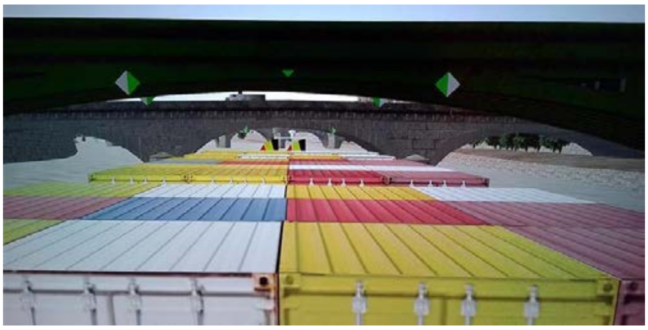

Figure 3. 3D external view of the non-aligned bridges.

- Bathymetry: this was the part under the waterline. It was reproduced from the bathymetric data and influences the hydrodynamic behaviour of the ship.

2.3 *Hydraulic conditions*

The current was implemented with TELEMAC, which is a software package that resolves the 2D water equations to model the water flow [5]. The mesh had a resolution of 10 m with a refinement of 5 m close to the banks and 2 m around the bridge piles. To obtain current velocities at the depth corresponding to the draft of the ships, a correction factor based on a logarithmic distribution of the velocities was applied. Hydraulic conditions from 0.82 m measured at the reference station Austerlitz (low water) to 4.30 m measured at Austerlitz (maximum water level for which navigation is currently allowed) were modelled with an increment of 0.10 m. Of note, the zero level at Austerlitz station corresponds to 25.92 m NGF-IGN69. The minimum water depth guaranteed at low water is 3.4 m.

The water surface was then varied in real time on the simulator to simulate the significant water level variation between the upstream and downstream direction depending on the current flow condition.

2.4 *Ship models*

In addition to the ship models of 11.45 m beam used in the first phase of the study [1], models of motorships of reduced dimensions, as listed in Table 1, were implemented in the simulator. The beam values were recommended by VNF based on an analysis of the fleet sailing in Paris.

The manoeuvring behaviour of each ship model was determined by a mathematical model which computes:

- hydrodynamic forces, propulsion and steering forces, shallow water effects, restricted water effects;
- aerodynamic forces;
- interaction with encountering and overtaking target vessels.

Table 1. Ship models

Transport	ECMT Class	Length [m]	Beam [m]	Draft [m]	Air Draft [m]
2 layers container		125	11.45	1.70	4.75
bulk		125	11.45	1.70	4.00
2 layers container		125	9.65	1.70	4.75
bulk		125	9.65	1.70	4.00
2 layers container	Va	110	11.45	1.70	4.75
bulk		110	11.45	1.70	4.00
2 layers container		110	10.55	1.70	4.75
bulk		110	10.55	1.70	4.00
2 layers container		110	9.65	1.70	4.75
bulk		110	9.65	1.70	4.00
2 layers container	IV	86	9.65	1.70	4.75
bulk		86	9.65	1.70	4.00
bulk		68	7.25	1.70	2.90
bulk		68	6.60	1.70	2.90
bulk		55	6.60	1.70	2.90

These new ships were obtained by scaling down existing models developed and validated in-house [6]. The propulsion and geometrical characteristics of these ship models were based on reference ships representing the actual fleet.

2.5 *Skippers*

The real time simulations in this study were executed by professional skippers who had ample experience with navigation in Paris. One skipper was particularly familiar with 110 to 180 m long bulk convoys with a beam of 11.45 m. Another skipper was particularly familiar with container ships of 86 m x 9 m and smaller. Prior to the actual simulations, the skippers spent a day on the simulators during which they could provide feedback on the realism of the new mathematical manoeuvring models. The skippers shared their experience before, during and after each simulation. The human factor was taken into account by repeating the scenarios with two different skippers at the water level identified as potential limit. The scenarios were also assigned to skippers based on their particular experience (push convoy, container ships…) so that the different nuances linked with sailing with different ship types are also taken into account.

3 DETAILED STUDY

3.1 *Simulation protocol*

The results of the first phase of the study with 11.45 m-wide ships showed that the limits for safe navigation were reached at a lower water level than the level up to which navigation is currently allowed [1]. When the results of the first phase were presented to VNF and stakeholders, skippers claimed that it was possible to sail at much higher water levels with the actual fleet (i.e. with smaller beam). Therefore, the operational limits identified with 11.45 m wide ships were used as a starting point to define the hydraulic conditions for which the simulations had to be carried out with narrower ships in order to investigate the feasibility of navigation at higher water levels and current flows. However, based on the feedback received by skippers prior to the simulations, a different bottleneck as the one identified during the first study was expected for the smaller ships. Hence the protocol did not consist only of repeating the simulations at the bottleneck encountered by the wider ships but also to sail further down the itinerary until the next bottleneck.

3.2 *Debriefing and skippers feedback*

After each real time simulation, the skippers were invited to the control room to give their opinion and share their observations about the manoeuvres that were performed so that the nautical expert could already make a judgement of the accessibility level. The difficulty as well as the safety of the manoeuvre was rated on a scale from 1 to 6. In this study, the skippers could immediately compare what they experienced on the simulator with their real life experience as investigated scenarios were similar to situations encountered in real life. Skippers could share their experience of water level limits set by the crew on their own vessels (e.g. container ship of 86 m x 9 m). These limits appear to be much lower than the maximum water level allowed by the regulations (i.e. lower than 4.30 m measured at the Austerlitz gauging station) because the skippers knew the itinerary very well and were able to estimate the safety limitations related to the current flow and geometric restrictions without taking any risks. Preliminary results obtained during the simulations were useful to drive the protocol and select the testing conditions in an optimized way, but the final results depended on the comparative and objective analysis of all the parameters conducted after a detailed post-processing of the simulation runs that was based on the safety criteria that are described in Section 3.3.

3.3 *Safety criteria*

Different criteria were used to evaluate the difficulty and safety of the manoeuvres. At high water levels, the most critical parameters in the crossing of Paris were the horizontal distance between the ship and the line corresponding to the air draft of the ship and the vertical distance between the ship and the bridge. Three other parameters were monitored as well: the reserve of the propeller, the reserve of the bow thruster and the reserve of the rudder. In general, the reserve of a control parameter n, written as R_n, was the reserve that is available in case a problem occurs and was defined by Eq. [1] in function of the mean value $\hat{n}$ and the maximum value n_{max} of the parameter n over the duration of a simulation.

$$R_n = 1 - \frac{\hat{n}}{n_{\max}} \tag{1}$$

For the three criteria mentioned above, the control parameter n was equal to the number of revolutions of the main propeller, the number of revolutions of the bow thruster and the rudder angle respectively.

Another parameter that was used as a criterion to assess the safety margin of a manoeuvre was the number of rudder variations (in °/s) derived from the mean rate of turn. This parameter was a good indication of the level of stress that the pilot experiences during the manoeuvre. Three other parameters were also considered in the analysis: under keel clearance (UKC), the vertical distance between the ship and a bridge and the distance to moored ships.

For comparability purposes, the accessibility level was evaluated based on the same criteria and colour code as the one defined for the first study [1].

When the difficulty and safety of the simulations had been evaluated using the safety criteria, an accessibility level was attributed. A manoeuvre was considered as impossible when at least one of the safety criteria turned red. For each simulation, comments were added by the nautical expert and feedbacks from the skippers, given immediately after each simulation, were included.

The results were grouped together in different data sheets, providing an overview of the results per ship and per sailing direction (upstream or downstream). Figure 4 gives an example of what such a sheet looked like for a 125 m x 9.65 m container ship. It can be seen that the analysis indicated that navigation was impossible in the first section of the simulated trajectory from water level n°3 onwards.

Figure 4. Extract from a simulation sheet for a 125 m x 9.65 m container ship sailing downstream with a draft of 1.7 m. Analysis of the section n°1 (between the two isles), n°2 (Pont Neuf) and n°3 (Pont des Invalides) of the waterway.

3.4 *Analysis of the impact of reduced beam*

The first results showed that ships with beams smaller than 10.00 m can sail under the bridge Pont Neuf at much higher water levels than ships with a beam of 10.55 m and 11.45 m. Indeed, at the limit identified for 11.45 m-wide ships, 9.65 m-wide ships did not need to be perfectly aligned to pass the bridge. However, another bottleneck was identified further downstream the itinerary, at the bridge Pont des Invalides which has the lowest headroom in Paris. Indeed, due to its flatter shape, the available width under the bridge Pont des Invalides was wider at low water levels than under the bridge Pont Neuf. As the headroom was lower under the bridge Pont des Invalides, ships were limited geometrically at this bridge at high water levels, as shown in Figure 5. For example, the 9.65 m wide ship models were geometrically limited to a water level of 3.60 m at Austerlitz (considering a margin of 50 cm between any point of the ship and the intrados of the bridge). At a water level of 3.40 m at Austerlitz, ships had an additional 1 m of width available on each side, thus increasing the manoeuvring space to pass underneath this arch.

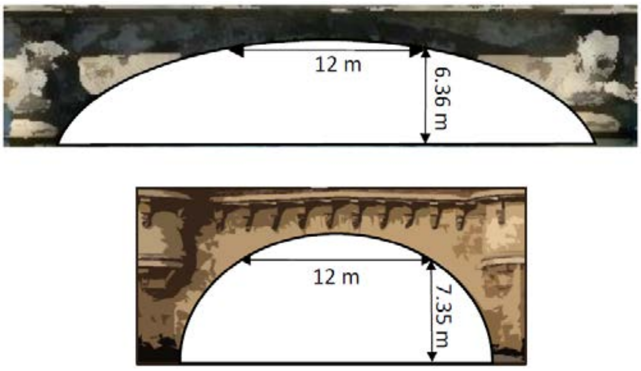

Figure 5. Transverse view depicting the headroom under the bridges Pont des Invalides (top) and Pont Neuf (bottom) for a width of 12 m (simplified sketch).

When sailing close to the geometric restriction, ships needed to pass while being perfectly aligned under the bridge Pont des Invalides. Due to the presence of the arch bridge Pont Alexandre III, which was located only 200 m further upstream, the ship would have had to make a quick zig zag manoeuvre to be able to pass while being centred under both bridges. This manœuvre was not feasible for container ships of 86 m and any ship longer than 110 m.

Container ships of 125 m with a beam of 9.65 m encountered also some difficulties in between the two islands due large drift effect induced by high current speeds at the exit of the second bend where the arch bridge Pont d'Arcole is located which was the first bottleneck for this ship. Those difficulties could also be observed with the other tested ships, nevertheless, they happened at higher water levels than the limits identified at the bridge Pont des Invalides and were not considered as a bottleneck for those other ships.

3.5 *Challenges*

3.5.1 *Air draft definition*

At very high water levels, the headroom under bridges was reduced so much that skippers adapted their trajectory based on the air draft of each ship model and therefore this parameter needs to be defined with care prior the simulations and in the analysis of the results. For instance, bulk carriers might be able to sail with some eccentricity under bridges while container ships would have needed to be centred during the full passage, as showed in this phase of the study with the succession of the two arch bridges Pont Alexandre III and Pont des Invalides.

The maximum water level at which a ship would be able to sail would strongly depend on the actual air draft of the ship and the ballasting possibilities. Hence, when presenting the results to skippers, questions about the validity of conclusions for ships with reduced air draft or increased ballast were raised. However, both air draft and ballast can vary significantly for a ship and standards are difficult to find, as investigated by PIANC [7].

For this study, the air draft of the different ship models had been tuned after consultation with the client and the pilots involved in the study in order to be compatible with the air draft of the actual fleet in Paris. Of note, the minimum height of the ship wheelhouse may vary from one region to another. For instance in Belgium, class Va vessels generally have a higher wheelhouse (e.g. 8 m measured from the keel) than in France. The wheelhouse of the self-propelled container ship model used in this study could be lowered almost to the level of the containers, so that the wheelhouse top was at 6.45 m measured from the keel and the top of the containers layers was at 5.80 m measured from the keel. This gave very low visibility for the skipper, which was critical because the use of radar was forbidden in Paris. In practice, under low bridges, the skippers would usually lower the wheelhouse as low as possible and steer the ship by passing their head through a hatch, as described in the first phase of the study [1]. The height of the self-propelled bulk carriers had been set at 5.70 m measured from the keel (i.e. with an air draft of 4.00 m for a draft of 1.70 m). Hence, in this study, the air draft was defined by the height of the wheelhouse.

For smaller beams, for which the bottleneck is related to simple geometric consideration under the bridge Pont des Invalides, skippers could easily estimate their water level limits depending on their air draft. However, for wide ships the maximum water level limits were more difficult to estimate by considering only the air draft of the ship. Indeed, the bottleneck was related to difficulties to pass aligned due to the small available width under the bridge Pont Neuf whereas ships with a smaller beam could sail with a large drift angle and pass without being aligned.

Although the air draft is ship dependent, simulations investigating bottlenecks above the waterline (e.g. arch bridges) should be executed in those loading conditions where the air draft is expected to be at a maximum on the waterway in order to be able to draw generic conclusions.

3.5.2 *Human factor*

As described in the first phase of the study [1], skippers used different techniques to tackle a specific bottleneck. In this phase of the study, the influence of human factor could be identified between the bridge Pont Alexandre III and the bridge Pont des Invalides. Since the headroom of the bridge Pont Alexandre III was higher than under the bridge Pont des Invalides, skippers with ample experience with this passage could avoid the zigzag manoeuvre by sailing as off-centre as possible under the bridge Pont Alexandre III to be able to pass perfectly aligned with the bridge Pont des Invalides, as shown in Figure 6. This technique required a good estimation of the available space under the bridge Pont Alexandre III and was obviously limited to certain water levels and certain ships and was strongly dependent on the air draft. It is clear that allowing navigation at such water levels for these ships to new skippers with no prior experience of sailing in Paris who might not anticipate these bottlenecks, would be dangerous. Therefore a certification system (in which the waterway manager would make an exception for a ship exceeding the maximum dimensions allowed), training strategy (e.g. by using ship handling simulators) and other recommendations were formulated when the accessibility could not immediately be validated based on simulation results.

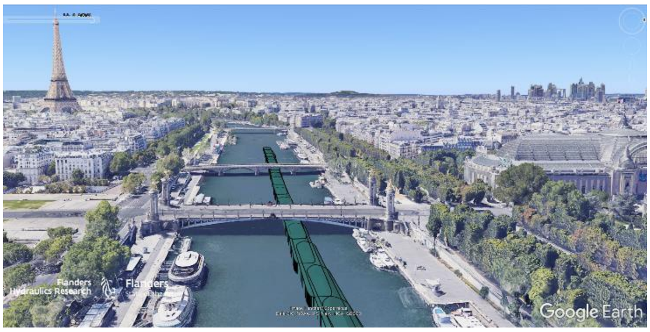

Figure 6. Simulation of a 9.65 m wide ship sailing with an eccentricity under the bridge Pont Alexandre III to be perfectly aligned with the bridge Pont des Invalides.

4 DISCUSSION OF THE SIMULATIONS

The results of the fast time simulations and real time simulations of the two phases of the simulation study (i.e. this phase and the first phase [1]) were combined to recommend a level of accessibility for each of the sections of the 12 km long trajectory. The main bottleneck for 11.45 m- wide ships was sailing under the bridge Pont Neuf, where the ship must arrive perfectly aligned due to the restricted width. This was especially difficult to achieve when sailing downstream after passing the bends in between the two islands and the non-aligned bridges. Ships with a beam of 10.55 m could sail at slightly higher water levels but encountered similar difficulties under the bridge Pont Neuf. For ships with a beam of 9.65 m, the bridge Pont Neuf was not the main bottleneck anymore because the ships could sail with a certain eccentricity under the bridge. However, the low headroom of the bridge Pont des Invalides further down the itinerary limited the maximum water level at which a ship could sail and became the first bottleneck. Shorter ships (i.e. length < 110 m) could pass while being centred and are therefore only limited by their air draft. Longer ships had to sail in a zigzag manoeuvre due to the proximity of the upstream bridge Pont Alexandre III. Depending on the air draft of the ship and the experience of the skipper, the zigzag manoeuvre could be avoided by sailing off-centered under the bridge Pont Alexandre III. The succession of a sharp bend and two arch bridges was however considered as very difficult and not feasible for the average skipper. As a successful passage involved being repeated on the simulator and a certain advance knowledge of the problems involved, the manoeuvre could not be considered as acceptable unless some measures were taken. Hence, the critical water level could not only be based on simple geometric considerations for the longer ships. For ships with shorter beams the limitations were mainly geometric and could be estimated by the skippers before deciding to cross Paris.

After the two phases of the study, the accessibility level of the actual fleet could be assessed for the full crossing of Paris in order to easily visualize the operational limits (i.e. water levels) of the different ships, as shown in Figure 7 and Figure 8. This helped the waterway manager in assessing the relevance the present regulations for sailing in high water conditions (which are based on ship length only) as well as their possible optimization. The results were then discussed with VNF and stakeholders.

From figure 7, it can be seen that the simulations executed during the first study were in agreement with the present regulations. Only bulk carriers of 110 m x 11.45 m would be able to sail above the current limit of 1.60 m measured from the Austerlitz gauging stations..

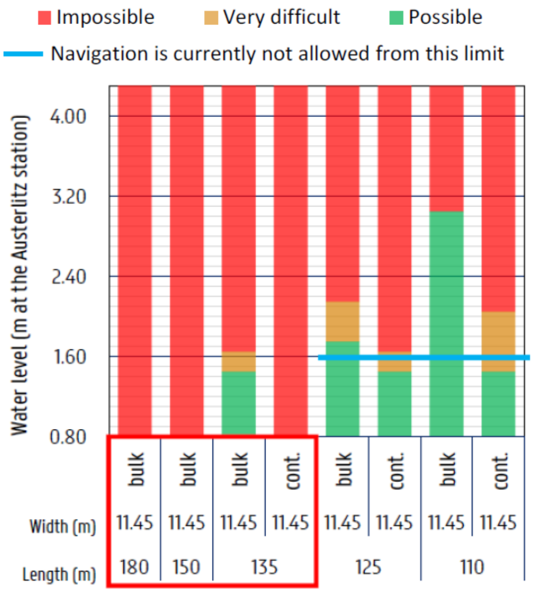

Figure 7. Synthesis of the first simulation study showing the operational limits (i.e. water levels) for the possible future fleet in Paris.

From Figure 8, it can be concluded that the regulations based on length were too restrictive for ships with a beam smaller than 10.00 m. Ship with a beam of 9.65 m and a length shorter or equal to 110 m were only limited by their air draft due to the low headroom under the bridge Pont des Invalides (simple geometric consideration). Ships with a length shorter or equal to 68 m and a beam shorter or equal to 7.25 m could sail at the maximum water level currently allowed (4.30 m at the Austerlitz station) thanks to their reduced beam and air draft which allowed them to pass the bridge Pont des Invalides. Of note, the simulations showed that a difference of 5 m in length did not have a significant influence, hence only the results of the 110 m ship were presented and were applicable to the 105 m ship.

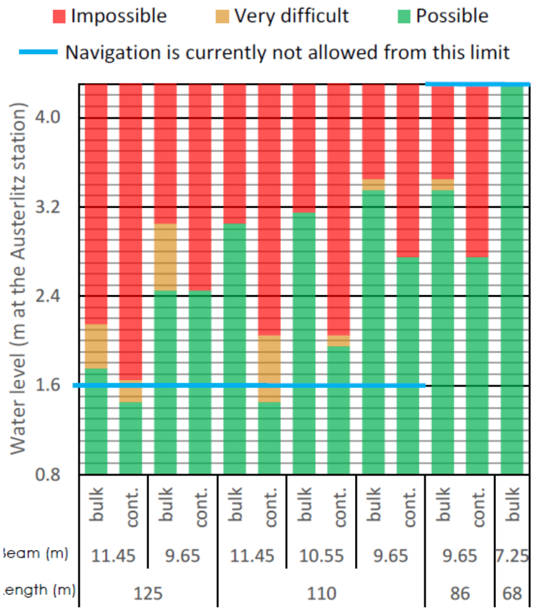

Figure 8. Synthesis of simulation studies showing the operational limits (i.e. water levels) for the actual fleet in Paris.

Case by case studies with an optimized ship (e.g. with a reduced air draft and increased ballast) were furthermore recommended to optimize the navigation condition, while respecting safety margins at all time, for a ship sailing regularly in the area for which operational limits could be accurately defined. For example, cruise companies set their own water level limits for each passenger ship in Paris using experience and in-situ measurements. However, such scenarios were beyond the scope of this study.

5 CONCLUSIONS

A study was carried out to optimize the operational limits for which present and future vessels of varying types and dimensions cross Paris. Fast time and real time simulations were executed at Flanders Hydraulics for different water levels of the river with experienced skippers. The first phase of the study [1] showed that for 11.45 m wide ships the main bottleneck was located at the narrow width under the bridge Pont Neuf, where ships had difficulties aligning in order to pass safely. The second phase of the study, presented in this paper, showed that this passage was not a bottleneck for ships with beams lower than 10.00 m but the bottleneck jumped further downstream to the bridge Pont des Invalides, due to the low height of the bridge and the difficulty to pass perfectly aligned just after a sharp bend.

A critical water level up to which ships would safely sail could be successfully identified for the different ship models that were tested and it appeared that the small ships were mainly limited by the air draft due to the low headroom under the bridge Pont des Invalides which geometrically restricted certain ships to pass underneath even if navigation was allowed.

Moreover, recommendations on the optimization of the operational limits by means of further measures were formulated. To open the navigation to larger ships or at higher water level, regulations could be subject to a system of certification granted by the waterway authorities based on the vessels characteristics and the level of familiarity of the skipper with the waterway. Training on simulators could also help in familiarising skippers with the bottlenecks and to have the skippers certified to cross Paris safely at high water levels. Finally, tests in real life conditions could also be organised to increase progressively the water level threshold. The results of simulations showed the possibilities for improvement of the accessibility level if such measures were taken (orange color on Figure 6 and 7). However, it should be noted that the safety margins of the validated scenarios were already greatly reduced and very close to the limit for the navigation of inland ships under narrow bridges.

After simulations executed with ships of reduced beam (closer to the actual fleet characteristics), the question arose whether the accessibility level of ships with reduced air draft could be better. However, this is a parameter which varies a lot depending on the ship type and which might be complex to implement in practice. Similar question arose about the loading conditions. When crossing Paris at high water levels, the critical loading condition was the empty condition. However, some skippers indicated that they could navigate in loaded conditions with higher drafts than those tested (and therefore lower air drafts). These two cases were outside the scope of this study and were therefore not investigated.

The results presented in this paper were presented to the waterway authority (VNF), stakeholders and end users. VNF would use the results to adapt the regulations.

ACKNOWLEDGEMENTS

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