

# Optimized turning basin design for inland waterways

Marc Mansuy <sup>1,\*</sup>, Maxim Candries <sup>1</sup>, Katrien Eloot <sup>2</sup>, Sébastien Page <sup>3</sup>, Roeland Adams <sup>3</sup>,  
Xavier Thorel <sup>4</sup>, Guillaume Decroix <sup>4</sup>

<sup>1</sup>Ghent University, Ghent, Belgium

<sup>2</sup>Flanders Hydraulics Research, Antwerp, Belgium

<sup>3</sup>IMDC nv, Antwerp, Belgium

<sup>4</sup>Voies Navigables de France, Lille, France

\*Corresponding author.

E-mail address : [marc.mansuy@ugent.be](mailto:marc.mansuy@ugent.be)

## 1 Abstract

Concept design guidelines for ship turning basins can often not be met in practice due to environmental, economic or geotechnical restrictions. In those cases, a detailed design procedure is followed to develop an optimized turning basin geometry within the environmental constraints. Real-time ship manoeuvring simulations are then used to evaluate the manoeuvres in the proposed geometry. However, such a detailed design procedure is costly, especially if a large number of simulations is required. In order to restrict the number of simulations, the waterway authority Voies navigables de France (VNF) ordered a study to find a generic and optimal design for a turning basin which could be suitable for the upgrade of the northern part of their inland waterway network. To this end, turning manoeuvres of two typical inland navigation vessels were simulated in real time in different hydro-meteorological conditions. The study was conducted in three stages. In a first stage, the manoeuvres in traditional circular

and trapezoidal turning basins of different sizes were executed and analysed. In a second stage, optimized turning basin geometries were developed and the turning manoeuvres in those optimized geometries were then analysed in a third stage. Based on the results of the analysis, a stepwise approach is proposed to select an optimized turning basin geometry according to the conditions present on site. It is considered that this stepwise approach for designing turning basins reduces the amount of real time simulations that are required when upgrading a waterway network.

## **2 Introduction**

A turning basin is an area in a port or waterway where ships can turn safely. There are several guidelines for the concept design of turning basins, but in general they are designed with a circular (for geometric reasons) or trapezoidal (for constructional reasons) shape, the size of which depends on the length of the design vessel (PIANC, 2019). The turning basin width depends on the turning method (fixed or free) and can be large in certain conditions, for example in adverse environmental conditions or when no tugs are available. Turning areas can also be lengthened on rivers with current. Along the banks of a channel or river, the width of the channel or river may need to be widened to allow an appropriately sized turning area (PIANC, 2014). The turning area can be built on only one or both banks of the navigation channel.

In the detailed design phase, the dimensions of the turning area can be reduced. Ship manoeuvring simulators are typically used at this stage. Kornacki and Galor point out that this can be complemented by an optimization process that takes costs into account (Kornacki and Galor, 2007). Kornacki analyzed a series of simulations in different current conditions to study the effect of the current on the dimensions of the area that is required to perform turning manoeuvres (Kornacki, 2010). In order to delimit the manoeuvring area of a turning basin, Kornacki proposed a polar method (Kornacki, 2011b) and discussed safety factors that can be

taken into account (Kornacki, 2011a). Kim et al. (Kim, Lee and Park, 2012) carried out simulations with seagoing vessels under different conditions in order to determine the optimal size of a turning basin in the port of Ganjung on Jeju Island

Paulauskas et al. present optimization methods for turning basins that consider geometrical factors and the time required to complete the manoeuvres (Paulauskas *et al.*, 2016). Within a waterway network, locations where ships can turn can become bottleneck locations (Kabir *et al.*, 2022), so that the placement of turning basins requires careful planning and consideration of traffic flows.

In this paper, the effect of turning basin geometry and hydro-meteorological conditions (i.e. wind and current) on the turning manoeuvres of inland navigation vessels is presented. The study was carried out in the framework of upgrading the Nord-Pas-de-Calais ECMT Class V waterway network (northern part of France).

The Nord-Pas-de-Calais ECMT Class V waterway network (framed in black on Fig. 1) will play a major role in linking the Seine River basin via the Seine Nord Europe canal to the ports of Dunkirk, the inland navigation network of Belgium and its connected ports Antwerp and Rotterdam (Bour *et al.*, 2019).



Fig. 1. Seine-Scheldt project and the Northern part of the French inland waterway network (black frame) (source: <https://www.seine-scheldt.eu/>).

The existing Nord-Pas-de-Calais Class V network does not fully meet the modern geometrical standards for canal design and construction. In order to prepare the network for the expected increase in traffic, Voies navigables de France (VNF) has commissioned a comprehensive analysis of the waterway network based on nautical studies. Part of this analysis consists of the research and design of a generic optimal turning basin for ECMT class Va (110 m x 11.4 m) and Va+ (135 m x 11.4 m) vessels, which could be used as input for a Master Plan for Turning Basins for the Nord-Pas-de-Calais network.



Fig. 2. Example of ECMT Va inland ship with 2 layers of containers.

To this end, real-time manoeuvring simulations were carried out to evaluate the accessibility level of turning basins geometries. The setup is given in Section 3. The turning manoeuvres are described and evaluated in section 4. In Section 5, a stepwise approach for the optimized design of ship turning basins is proposed.

### **3 Setup of the real-time simulations**

#### **3.1 Design vessels**

The simulation study was carried out with vessels representative of ECMT class Va (110 m x 11.40 m) that typically ply the waterway network in Northern France and Va+ (135 m x 11.40 m). Container ships with two layers of containers were selected to represent the worst-case-scenario (Fig. 2). This type of vessel is generally the most difficult to manoeuvre in wind conditions compared to bulk vessels due to their large windage areas, while still complying with the maximum air draft (5.25 m) on the Nord-Pas-de-Calais waterway network. Two

loading conditions were tested: a fully loaded condition with a draft of 2.5 m and a ballast condition with a draft of 1.7 m.



Fig. 3. Heights ship models: measured from the keel to the top of the second layer of containers (right) and measured from the keel and the top of the wheel house (left).

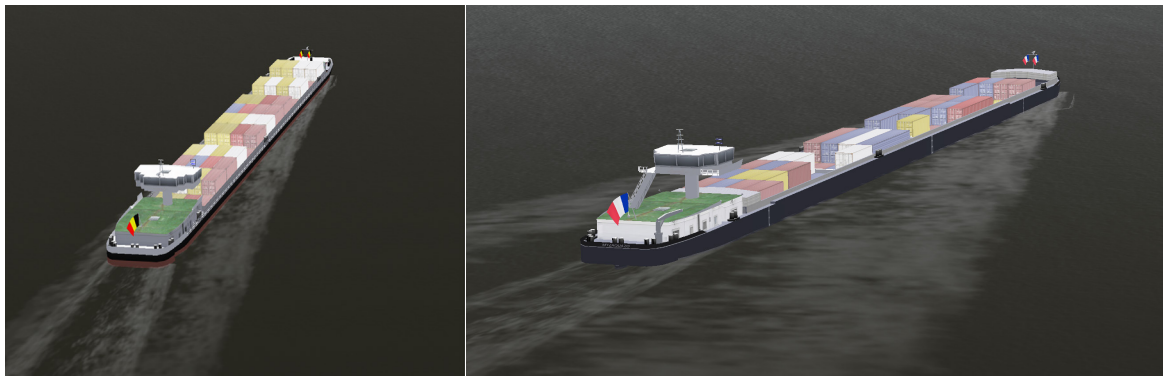


Fig. 4. Class Va ship model (left) and class Va+ ship model (right).

The main characteristics of the two design vessels and the two loading conditions considered in this study are presented in Table 3-1. Both design vessels are equipped with bow thrusters on the simulator. It should be noted here that this type of equipment is mandatory (CESNI, 2021) on any European vessel longer than 110 m (called Va+ in this case). Even though not mandatory, most class Va vessels are in practice equipped with bow thrusters. The power of the bow thrusters was the same for both vessels, but in real life, Va+ vessels can be equipped with more powerful bow thrusters. The class Va is equipped with a single propeller – twin blade rudder system (Eloot, Delefortrie and Vantorre, 2012a). The class Va+ vessel is equipped with a twin propeller – twin blade rudder system.

Table 3-1. Particulars of the design vessels for two loading conditions.

ECM T class	Transport	Loading condition	Length overall (m)	Breadth (m)	Draft (m)	Air draft (m)	Main engine (hp)	Bow thrust (hp)	Tonnage <sup>a</sup> [ton]	TEU <sup>a</sup>
Va	Containers (2 layers)	Fully loaded	110	11.40	2.5 /	3.95 /	180	650	1500	104
		empty			1.7	4.75	0			
Va +	Containers (2 layers)	Fully loaded	135	11.40	2.5 /	3.95 /	255	650	2300	136
		empty			1.7	4.75	0			

<sup>a</sup> based on (PIANC, 2020).

### 3.2 Concept geometries

Prior to the simulations, IMDC carried out a comparative analysis of the various designs of existing turning basins in France and abroad by means of literature reviews and interviews with waterway managers, nautical experts and skippers (Page *et al.*, 2023) in order to select the most suited geometries for the turning basins that would allow vessels to turn in typical hydro-meteorological conditions and restrictions encountered on the Nord-Pas-de-Calais network. In this pre-study, two basic geometries are selected for the turning basins to be tested on real-time manoeuvring simulators: a circle and an isosceles trapezium. For each basin type, two sizes are proposed: a large version in which a turn is expected to be relatively easy most of the time and a small version in which the turn is expected to be always possible, with less ease. For the small turning basin, the water depth is additionally reduced outside the navigation channel to take into account any possible sedimentation and thus a shallow area. The width of the navigation channel is set at 34 m, which is equal to the minimum width of the navigation channel at a water depth of 3.5 m that is guaranteed on straight sections of the class Va waterway network of Nord-

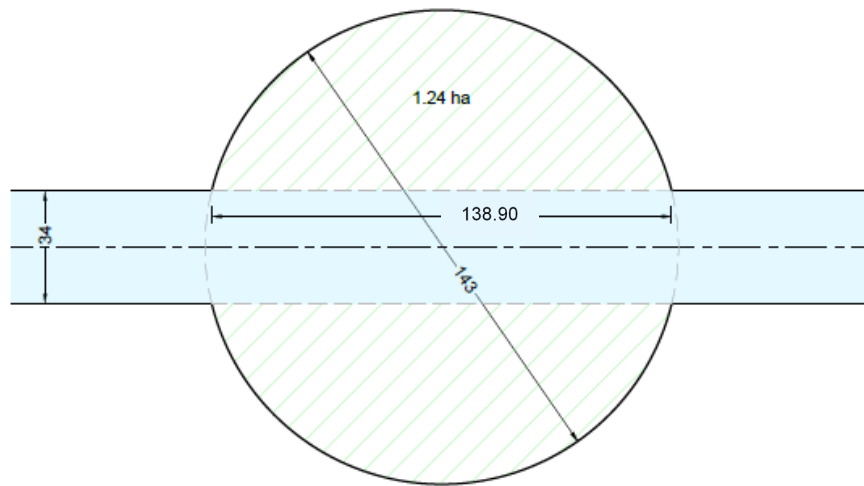
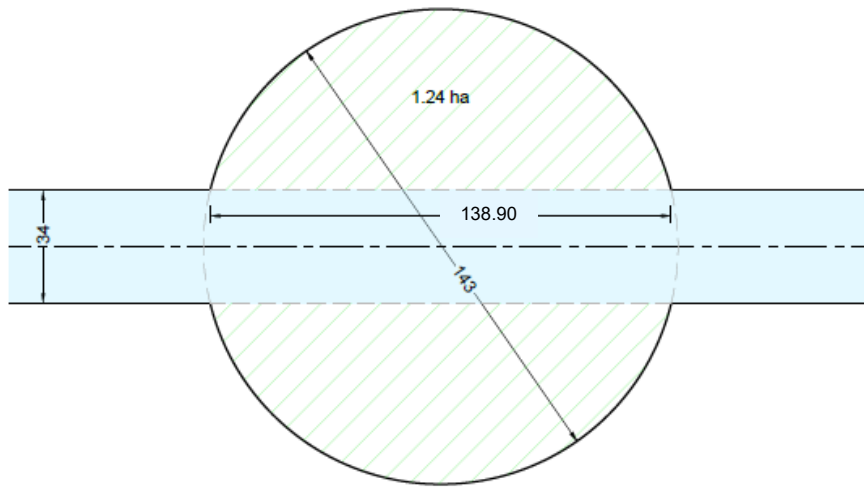
Pas-de-Calais. The characteristics of the two types of turning basins of different size are given in Table 3-2 for each design ship and illustrated in Fig. 5 and in Fig. 6 by the drawings made for the class Va.

Table 3-2. Dimensions of the concept geometries.

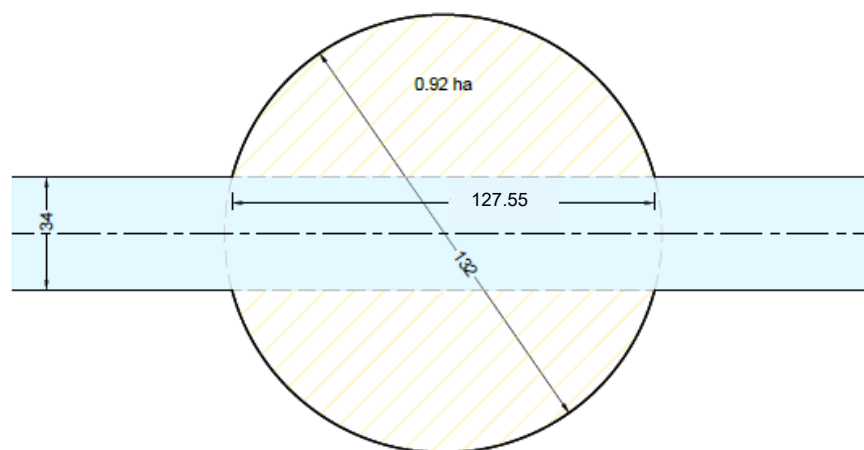
Shape	Circular		Trapezoidal	
	small	large	small	large
Size				
Dimensions	D = 162 m (1.2 L)	D = 175.5 m (1.3 L)	135 m from the channel axis, 30 m from the top (Va+)	149 m from the channel axis, 30 m from the top (Va+)
	D = 132 m (1.2 L)	D = 143 m (1.3 L)	110 m from the channel axis, 30 m from the top (Va)	121 m from the channel axis, 30 m from the top (Va)
Channel width	34 m	34 m	34 m	34 m
Water depth (inside channel)	3.5 m	3.5 m	3.5 m	3.5 m
Water depth (outside channel)	3.0 m	3.5 m	3.0 m	3.5 m
Base angle	-	-	50°	45°

Fig. 5. Circular turning basins, large (a) and small (b) versions for the class Va. The area outside the channel is hatched and measured in hectare (ha).

(a)



(b)



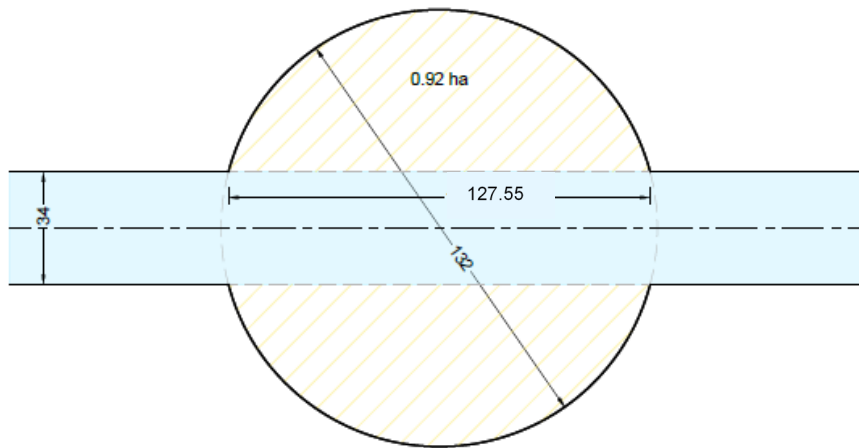
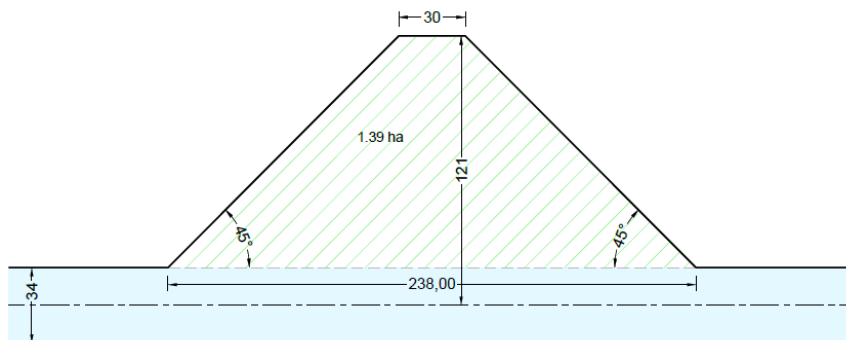
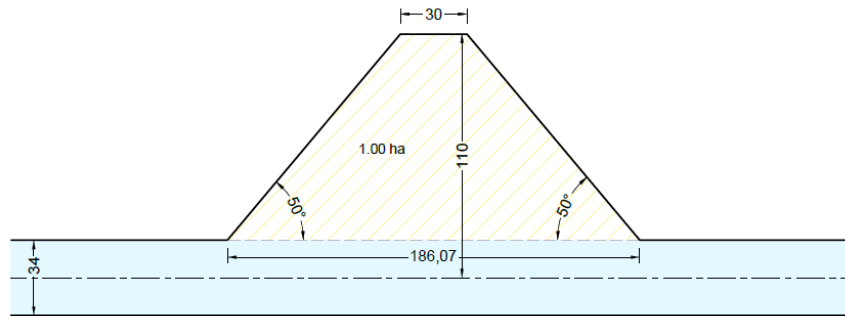


Fig. 6. Trapezoidal turning basin, large (a) and small (b) versions for the class Va. The area outside the channel is hatched and measured in hectare (ha).

(a)



(b)



These geometries were implemented in the simulator by modelling a bathymetry which is the part under the waterline influencing the hydrodynamic behaviour of the ship and an external view which is the part projected on screens allowing the skipper to orient himself.

For each geometry, the bathymetry was modelled with a 3D mesh using Delaunay triangulation with a resolution of 4 m x 4 m, with vertical banks and a constant depth of 3.5 m. For the small turning basins, a reduced depth of 3.0 m was modelled outside the channel. Above the waterline, a simplified 3D model was generated for the outside visuals of the simulations.

### 3.3 Manoeuvring simulator

The simulations were executed on a full mission manoeuvring simulator at Flanders Hydraulics Research, which has been specifically developed for inland navigation research. The inland navigation simulator is composed of a bridge with 210° front aerial view displayed on 52" LCD monitors, as shown in Fig. 7, with two rear monitors in the back. The bridge is equipped with ECDIS, controllable camera views and controllable bridge height.

Fig. 7. Manoeuvring simulator for inland navigation (Flanders Hydraulics Research, Belgium).



The manoeuvring behaviour of the design vessels used in this study is based on mathematical manoeuvring models. These mathematical models were derived from extensive model testing with a 1/25 scale model of a class Va ship in the Towing Tank for Confined Water at Flanders Hydraulics Research to provide data for the mathematical manoeuvring models at different drafts and under keel clearances (Eloot, Delefortrie and Vantorre, 2012b). The experimental data were then extrapolated from model scale to different full scale inland navigation vessels (ranging from an 85 m long class IV vessel to an 135 m long class Va+ vessel). The manoeuvring models were validated and modified by measurements on real vessels sailing on Flemish waterways (Verwilligen *et al.*, 2015). For this particular study, the mathematical models also take bank effects into account and have the option to include a bow thruster, the use of which can be restricted depending on the simulated scenario.

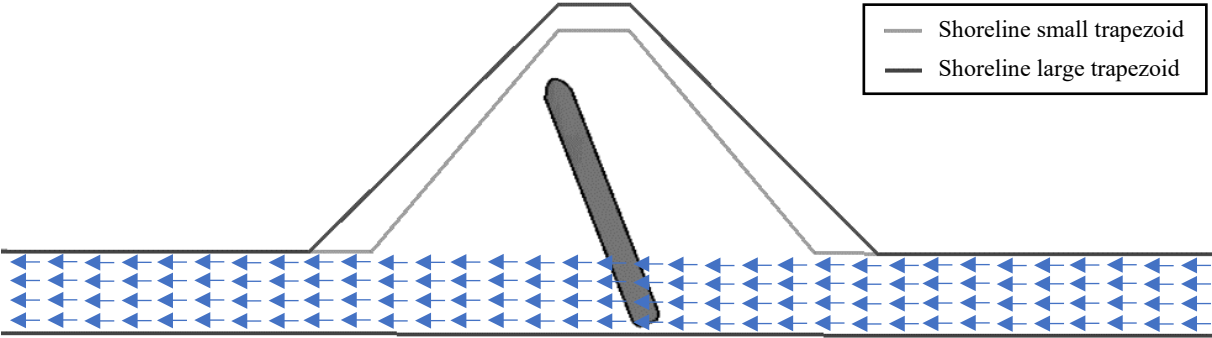
The real-time simulations in this study were executed by a professional skipper who has experience both with class Va vessels and on the Nord-Pas-de-Calais network. After each simulation a debriefing session was organized, during which the skipper could give his opinion about the simulation and the manoeuvres that were performed. The difficulty as well as the

safety of the manoeuvre is rated on a scale from 1 to 6. This feedback is taken into account when each manoeuvre is evaluated, along with objective evaluation criteria (cf. Section 3.5).

### 3.4 Hydro-meteorological conditions

The geometries presented in the previous section have been tested with current velocities and wind forces corresponding to severe but not extreme conditions in the Nord-Pas-de-Calais network. The maximum current is 0.4 m/s, which is the 95<sup>th</sup> percentile for the canalized rivers of the waterway network. The condition without current, which is representative for the canals, is also studied. The simulations have been executed with the ship approaching the turning area both in the upstream and downstream directions. The maximum wind force is taken as 5 Bft, which corresponds to the 95<sup>th</sup> percentile in the region of Dunkirk (seaside). The wind sheltering effect of banks and bridges is not taken into account. The model allows for some variability in wind intensity around the mean speeds (Von Karman spectral density). This gusty wind variation creates a more severe (but also more realistic) situation than a uniform wind. The condition without wind is also studied in order to study the effect of wind. Four different wind directions have been tested (from longitudinal to transverse to the channel). As a first approximation, the current was only applied in the channel and not in the basin itself (Fig. 5).

Fig. 8. Current field as implemented in the simulator (no current flow outside the channel).



### 3.5 Evaluation criteria

Different criteria are used to evaluate the difficulty and safety of the manoeuvres. The most critical parameter is the distance between the ship and the banks. Three other parameters that are used as criteria, are the reserve of the propeller, the reserve of the bow thruster and the variations of the rudder. It may be noted that the reserve of the rudder is not included because it is considered acceptable to use the maximum rudder angle during a turning manoeuvre. In general, the reserve of a control parameter  $n$  represents the reserve that is available in case a problem occurs and is defined by the following formulation:

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

With :

$R_n$  : Reserve of the control parameter  $n$

$\hat{n}$  : Mean value of the parameter  $n$

$n_{max}$  : Maximum possible value of the parameter  $n$

For the three criteria mentioned above, the control parameter  $n$  is equal to the number of revolutions of the main propeller and the number of revolutions of the bow thruster. The accessibility of the turning basin can then easily be evaluated based on the criteria using a colour code. Table 3-3 indicates the parameters ranges for each colour of the colour code. A turning manoeuvre is unacceptable whenever at least one of the criteria turns red.

Table 3-3. Evaluation criteria.

Accessibility level	Distance banks (m)	Reserve main propeller	Reserve bow thruster	Rudder angles variations (°/s)
Inacceptable	0 m - 1 m	< 10%	< 10 %	> 4°/s

Acceptable	1 m - 3 m	10 % - 40 %	10 % - 30 %	2°/s - 4°/s
No constraints	> 3 m	> 40 %	30% - 100%	< 2°/s

In addition to the indicators listed above, a characteristic duration of the turning manoeuvre is also given for comparison between the different scenarios. This time is calculated from the moment when the midship position was 200 m away from the centre of the basin (and close to the starting point of the simulations) to the moment when the ship resumed normal navigation in the channel in the opposite direction. The ship speeds at the start of the simulations were between 6 and 8 km/h (which were approach speeds requested by the skipper).

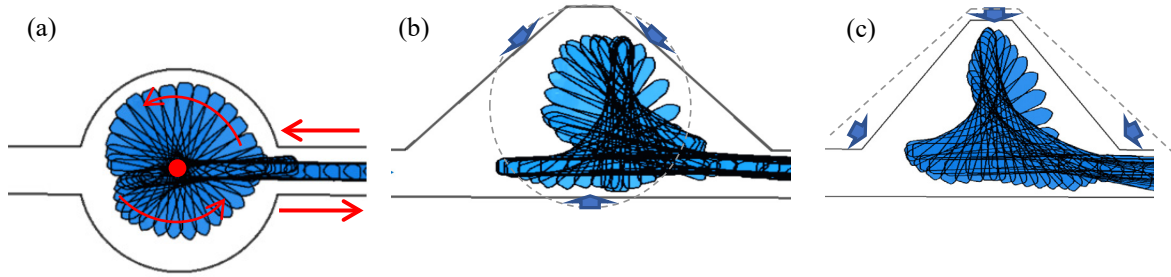
## 4 Evaluation of the turning manoeuvres

### 4.1 Description of the manoeuvre

Typical turning manoeuvres in confined turning areas are shown in Fig. 9 and are described in detail in this section based on the record of the ship control parameters (time series) and track plots of the manoeuvre obtained from the simulations. These data allow to better understand the behaviour of the ship and its skipper.

The first observation is that in a confined turning area the ship adapts its trajectory based on the boundaries of the basin (see Fig. 9(a) and Fig. 9(b)) and tends to turn in a circular shape. Moreover, by considerably constraining the dimensions of a turning area, the ship does not turn in a circular shape anymore and uses the available space as much as possible, sailing closer to the boundaries at slower speeds (see Fig. 9(c) ).

Fig. 9. Turning manoeuvre simulated in confined turning areas with no wind and no current (small circular basin ( $\varnothing 1.2L$ ) (a), large trapezoid (b), small trapezoid (c) ).

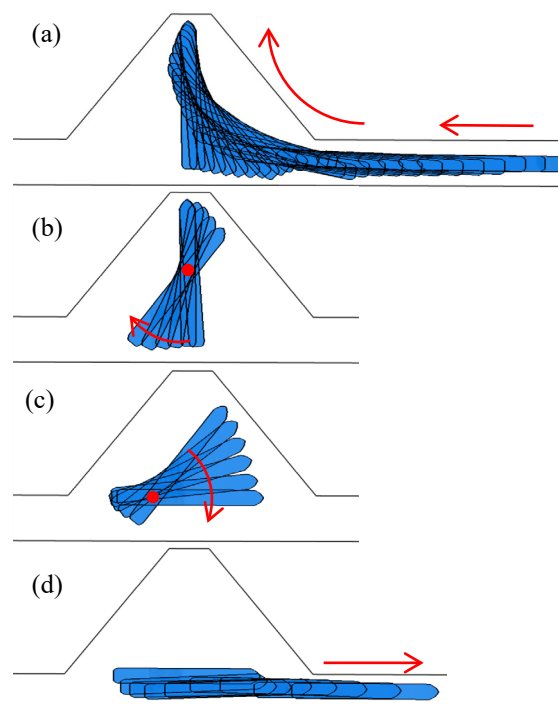


In a centred circular basin, the skipper slows down once it has fully entered the basin by turning slightly out of the channel and approaching the bow toward one side of the basin. He then rotates the ship using the maximum rudder angle,  $80^\circ$ , in combination with the main propeller and bow thruster to maintain a zero longitudinal speed and to turn as fast as possible following the circular contours of the basin until the ship is aligned with the channel in the opposite direction. Finally, the ship resumes its cruising speed as soon as it leaves the basin. Such a manoeuvre is illustrated in Fig. 9(a) with the pivot point in red. The dashed lines indicate the reduction of space between a large trapezoid and a small circle in Fig. 9(b) as well as the reduction of space between a large trapezoid and a small trapezoid in Fig. 9(c) and its effect on the ship trajectory.

In a trapezoidal basin, the turning manoeuvre is similar to a turn short round manoeuvre that a seagoing vessel equipped with a right hand fixed propeller would perform taking advantage of the transverse thrust generated by the propeller when the engine is reversed (Seo, 2017). The difference is that an inland vessel uses a complex combination of large rudder angles, main engine and bow thrusters to generate transverse thrust providing a better manoeuvrability than seagoing ships. Assuming that the skipper wants to turn to starboard and reverse, the skipper will first turn toward the small base of the trapezoid using  $45^\circ$  rudder angle to starboard and the main propeller with engine ahead (Fig. 10(a) ). When the ship is perpendicular to the channel (Fig. 10 (b) ), the skipper then gives a kick engine astern and rudder  $80^\circ$  to port to stop the ship and initiate the turn in combination with the bow thruster moving the pivot point slightly towards the bow. The skipper then uses the bow thruster to bring the bow toward the channel

in combination with engine ahead and rudder  $80^\circ$  to port to counteract the rotation and keep the stern as fixed as possible (Fig. 10(c)) and bring back the bow parallel to the channel (the pivot point moves toward the stern). Finally, the skipper uses the main engine and small rudder angles to come back to the centre of the channel ( Fig. 10(d) ).

Fig. 10. Turning manoeuvre of a class Va simulated in a small trapezoidal turning basin with no wind and no current. Pivot point in red.



Due to the large number of parameters involved (ship class, geometries, hydro-meteorological conditions, basin positioning, etc.), the number of possible scenarios amounted to several thousands. Some of these scenarios were clearly not possible and could be rejected immediately, while some scenarios were clearly possible and could be accepted immediately. Simulations were then executed in three stages: a first stage which allowed to study the effect of different parameters (i.e. basin geometry, current, wind and loading condition), a second

stage that used the analysis of the first stage to optimize the trapezoidal geometries and a third stage in which the proposed optimized basin geometries were analysed.

**4.2 First stage – analysis of circular and trapezoidal turning basin geometries**

**4.2.1 Influence of basin geometry, current, wind and loading condition**

A selection of the 97 simulations executed in the first stage is shown in Table 4-1 to highlight the influence of basin geometry, current, wind and ship loading condition.

Table 4-1. Selected simulation results - first stage.

Basin	Ship	Current direction	Wind	Draft	Manoeuvre Duration (min)	Distance banks (m)	Reserve main propeller	Reserve bow thruster	Rudder angle variations (deg/s)	Accessibility level
Circular (small)	110 m	Downstream	No	1.7	7.9	1.3	59%	51%	2.00	Acceptable
Circular (small)	135 m	Downstream	No	1.7	10.2	1.6	52%	21%	1.19	Acceptable
Trapezoidal (small)	110 m	No	No	1.7	7.5	3.4	68%	47%	2.01	Acceptable
Trapezoidal (small)	135 m	No	No	1.7	11.2	2.4	52%	16%	1.79	Acceptable
Trapezoidal (large)	110 m	Downstream	No	2.5	10.0	1.5	63%	37%	1.41	Acceptable
Trapezoidal (large)	110 m	Upstream	No	2.5	11.8	1.3	25%	24%	0.88	Acceptable
Circular (large)	110 m	No	No	1.7	7.6	5.8	69%	60%	1.31	No constraints
Circular (large)	110 m	No	No	2.5	9.3	4.2	40%	51%	1.89	Acceptable
Circular (small)	110 m	No	5 Bft	1.7	6.4	0.1	57%	36%	2.45	Inacceptable
Circular (small)	110 m	No	5 Bft	2.5	8.1	2.3	47%	45%	1.44	Acceptable

Basin	Ship	Current direction	Wind	Drift	Manoeuvr Duration (min)	Distance banks (m)	Reserve main propeller	Reserve bow thruster	Rudder angle variations (deg/s)	Accessibility level
Trapezoidal (small)	110 m	No	5 Bft	1.7	9.2	2.3	53%	36%	2.17	Acceptable
Trapezoidal (small)	110 m	No	5 Bft	2.5	12.5	0.0	42%	32%	1.07	Inacceptable

During the simulations executed in the first stage, a difference in manoeuvrability between the two design ships could be observed. For example, Table 4-1 shows that the rudder angle variations are larger for the 110 m long ship (ECMT class Va) and that the bow thruster reserve is generally smaller with the 135 m long ship (ECMT class Va+). This can be explained by the fact that a Va+ vessel requires a more powerful bow thruster. Based on the minimal distance from the bank calculated over the duration of the manoeuvre, it is clear that the small trapezoidal turning basins tested exhibit less margin for the 135 m long ship than for the 110 m long ship. This immediately indicates that a detailed design cannot be based only on simple ship length scaling and that the effect of ship length needs to be taken into account.

In the case of trapezoidal basins, turning in the basin while sailing upstream is more difficult than turning while sailing in the downstream direction. This can be ascribed to the fact that in the upstream direction, the current is directed against the direction of the rotation of the stern during steps (a) and (b) shown in Fig. 10, causing the ship to drift toward the edge of the basin. When approaching the basin in the downstream direction, the current pushes the stern of the ships and makes it turn in the desired direction. This results in a smooth manoeuvre in the centre of the basin. Hence, the manoeuvre takes more time and the reserve is lower in the upstream direction than in the downstream direction.

The crosswind was identified as the most critical wind direction regardless of the type of basin (circular or trapezoidal). In that case, the manoeuvre is performed very close to the side opposite to the wind direction and with more intense use of the bow thruster and large variations of rudder..

In a circular basin and in the absence of wind, the fully loaded condition is the most critical because the manoeuvrability is reduced due to the increase of weight and the small underkeel clearance as compared to that of the empty condition. As a consequence, it can be noticed that the manoeuvre with a fully loaded ship takes more time to complete and that the reserve of the main propeller is low.

In the case of the circular basins and in the presence of wind , Table 4-1 shows that the ballast loading condition is the most critical. Indeed, the large air draft leads to an increased effect of the wind, which is not counterbalanced by the better underwater manoeuvrability obtained with a low draft. This results in a lower bow thruster reserve for the empty condition simulation.

In the trapezoidal turning basins, the fully loaded condition is the most critical in the absence of wind but also in its presence. Indeed, in a trapezoidal basin, the ship needs to turn before entering the basin and this manoeuvre is more difficult with the fully loaded condition as the reduction in manoeuvrability due to the increase of draft of a fully loaded vessel is predominant on the difficulty related to the increase of windage area of an empty ship.

#### 4.2.2 Analysis of the circular geometries

In the circular basins, simulations show that a turn is possible in every tested condition, provided that the transition between the navigation channel and the basin is smoothened. Fenders are also recommended to prevent any collision between the ship and the bank at the entrance to the basin. Indeed, as the skipper begins to turn in a circular basin, the stern of the ship is displaced toward the corner of the basin entrance. Because of the lack of visibility on

the rear part of the ship and the difficulty to control the distance between the stern and the bank, there is a risk of contact between the stern of the ship and the basin's entrance. In general, protection is also recommended inside the basin.

The large circular basin is accessible without constraints in empty conditions for both ships ( $V_a$  and  $V_{a+}$ ) whereas turning in the small circular basin is acceptable but difficult. Those dimensions can therefore be used as boundaries for the selection of the turning circle diameter (from a comfort level to a minimum safety level) depending on the available space. With the fully loaded conditions, the manoeuvre is difficult but acceptable in both basins sizes.

It should also be noted that, unlike trapezoidal basins where the skipper can avoid entering the basin with the main propeller and rudder (which are kept as much as possible in the deepest part of the basin), this is not possible in a circular basin. The effective maintenance of the guaranteed depths is therefore essential. Finally, it should be added that the approach zone of a circular basin does not require any particular clearance on the banks since the vessel navigates centred in the channel to the inside of the basin.

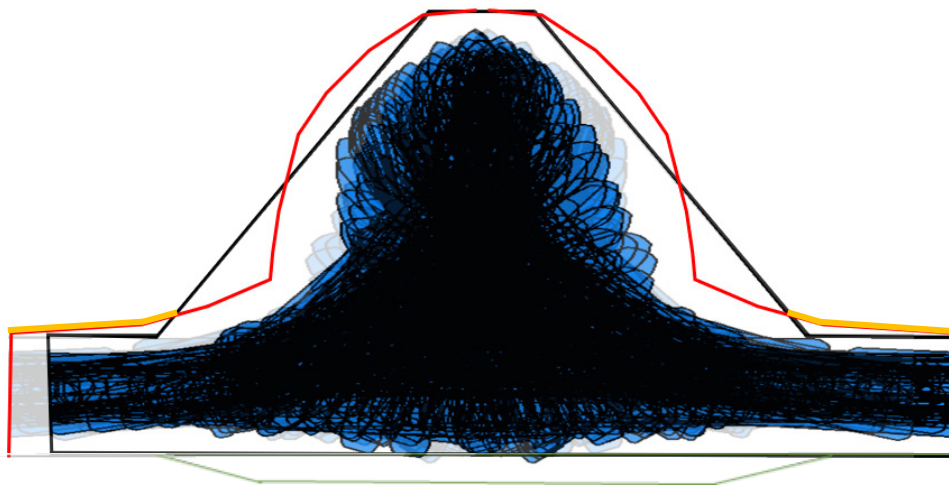
### **4.3 Second stage - optimization of the trapezoidal geometries**

The simulations executed in the trapezoids in the most critical hydrometeorological conditions (i.e. in current and wind conditions) showed that the smaller geometries were too constrained and optimizations were therefore proposed with the objective of allowing safe turning manoeuvres in the most critical conditions for a reduced cost compared to the larger sized turning basins. The optimizations were derived from an overlay of the simulation trajectories obtained in the first stage simulations. This process is illustrated in Fig. 11.

The simulations tracks presented in Fig. 11, shows that the ship can enter the turning area, but the bow cannot be positioned directly in front of the small base of the trapezoid so that the ship is pushed against the boundaries of the turning basin. More space is required for the ship to

make a safe turn toward the small base of the trapezoid. This can be done with a simple widening of the channel on the opposite bank so that the stern of the ship can rotate with less constraint and the ship does not need to enter too deeply in the trapezoid (as indicated by the green line in Fig. 11). However, if only one bank of the channel can be used for the construction of the turning basin (e.g., presence of infrastructure on the opposite bank, reuse of an existing turning area), the top of the trapezoid should be adapted and rounded so that the bow has more space to enter and rotate deeper in the trapezoid (as indicated by the red line in Fig. 11). The transition at the entrance has been optimized as well (as indicated by the orange lines on Fig. 11).

Fig. 11. Overlay of turning manoeuvres trajectories obtained with a class Va vessel in a small trapezoidal turning basin.

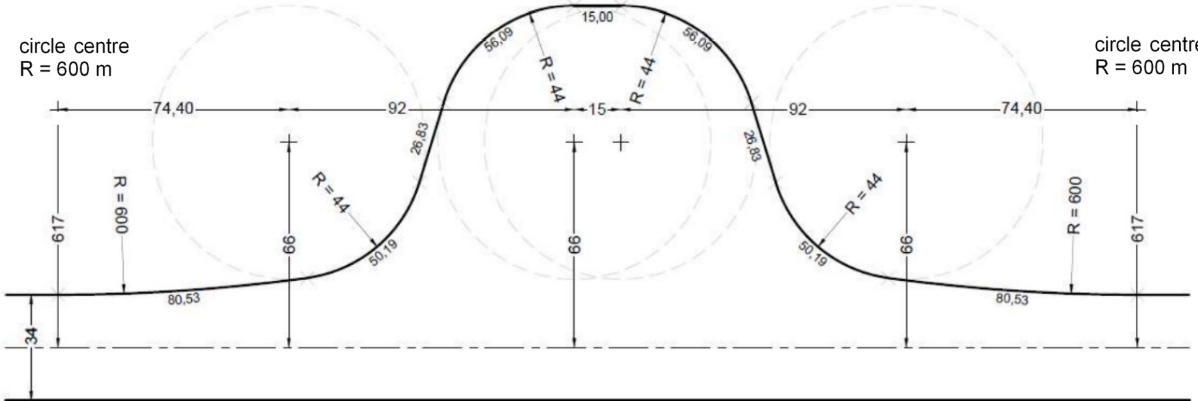


Two optimized geometries were thus proposed depending on whether the basin can be built only on one side of the channel or on both sides. These are called “Optimized Basin n°1”, shown in Fig. 12, and “Optimized Basin n°2”, shown in Fig. 13, respectively. The new geometries replace the original small trapezoid.

Optimized Basin n°1 consists of widening part of the small base of the small trapezoid. The top edges of this part are defined by two circles of specific diameter (see red line on Fig. 11 and

Fig. 12) so that the bow of the ship can turn easily during step 1 and 2 of the turning manoeuvre with the pivot point forward (cf. Fig. 10). The centres of the circles are separated by a certain distance to allow the ship to drift slightly to one or the other side of the basin depending on the current flow (Fig. 12). The optimization at the entrance of the turning basin is based on the turning radius of the ship when entering the basin (see orange and red lines on Fig. 11 and Fig. 12).

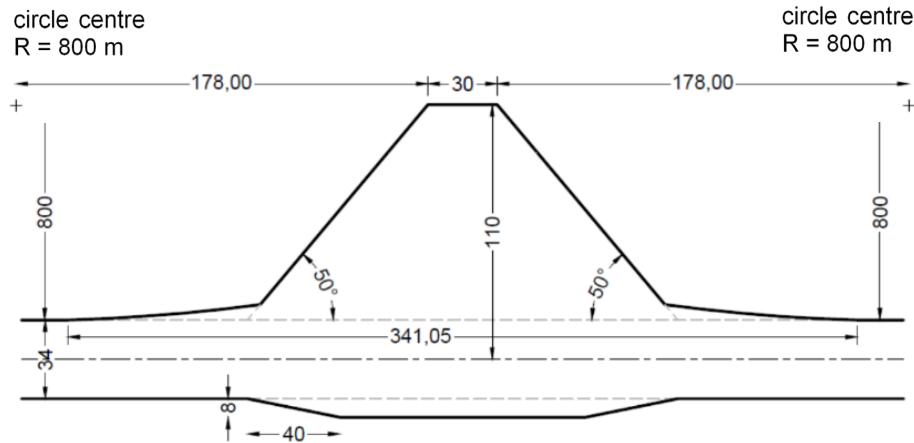
Fig. 12. Drawing of Optimized Basin n°1 for a class Va which is proposed if a turning basin can only be put on one side of the channel (distance in m).



Optimized Basin n°2 consists of widening the channel on the side of the large base of the small trapezoid on the so that the new base is positioned 5 m away from the envelop of the simulated trajectories (see green line on Fig. 11) and 8 m from the boundary of the channel (Fig. 13). This widening is connected to the main channel with a slope of 1:5 which is comparable to the slope which can be found at the inlet funnel of locks (PIANC, 2019). The optimization at the entrance of the turning basin is based on the turning radius of the ship when entering the basin (see orange lines on Fig. 11).

Note that the design and construction of Optimized Basin n°1 is more complex than the design and the construction of Optimized Basin n°2.

Fig. 13. Drawing of Optimized Basin n°2 for a class Va which is proposed for a turning basin which can use both sides of the channel.



#### 4.4 Third stage - Analysis of the optimized basins

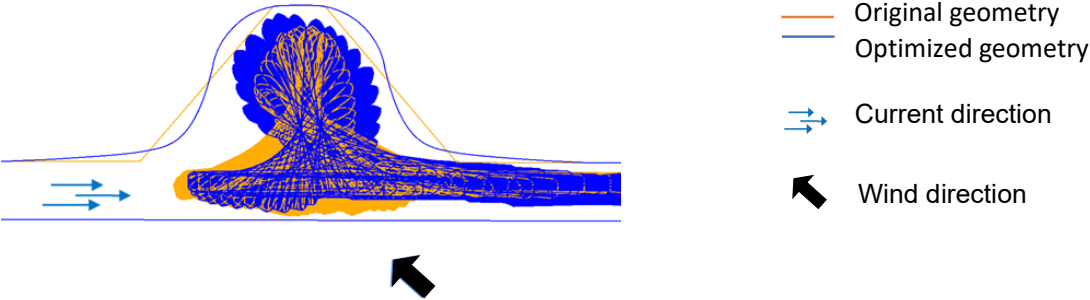
In the third stage of the study, the accessibility level of each optimized geometry was evaluated in different hydro-meteorological conditions in order to identify their limitations.

For empty ship conditions, contact with the banks could not be avoided in both optimized basins during turning manoeuvres simulated with both ship classes (Va and Va+) with current and with 5 Bft wind blowing from the small base of the trapezoid, perpendicular to the channel. With fully loaded 110 m long ships, turning manoeuvres are not possible in Optimized Basin n°2 in current and 5 Bft wind blowing from any direction. Turning with a fully loaded 135 m long ship is impossible in both optimized basins tested with current, regardless of the wind direction. Moreover, the simulations carried out with a 135 m long ship show that the large trapezoid is also not accessible in these conditions. Although the small base of the large trapezoid was initially set to 30 m for the 135 m long ship (ECMT class Va+), it was deduced from the simulations results that a widening to 40 m was necessary. It can be noted that turning in fully loaded conditions can be avoided in most cases. If not, turning manoeuvres with deep drafted container ships (2.5 m) should not be allowed in the tested geometries on sections with

current and in the most extreme wind conditions (5 Bft). For the Nord-Pas-de-Calais network, these scenarios are considered sufficiently rare (and/or avoidable) and such restriction is acceptable.

With the exception of wind blowing from the top side of the optimized geometries at 5Bft, the tests executed in maximum current and wind conditions showed the positive effect of the optimization on the small trapezoid, especially in terms of smoothness of the turning manoeuvres as illustrated on Fig. 14. It can also be noticed that a turn is possible because the transition between the navigation channel and the basin is smoothed, which was not the case in the original trapezoidal geometry, indicated by orange lines in Fig. 14.

Fig. 14. Overlay of the simulations in the original geometry and the optimized geometry n°1 in different hydro-meteorological conditions.

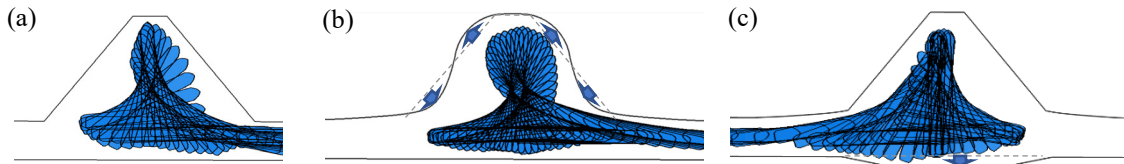


Moreover, it can be noticed that the skipper adapts his trajectory to the shape of the turning basin to use as much as possible the extra space available in Optimized Basin n°1 (see Fig. 15(b) ) and Optimized Basin n°2 (see Fig. 15(c) ) compared to the initial small trapezoid (see Fig. 15(a) ).

It can also be noted that the ship begins to turn before actually entering the basin. It is therefore recommended to keep the approach area free (e.g. no mooring area) for a distance of about  $1.5 \cdot L$  measured from the basin entrance, and a clear line of sight of  $3 \cdot L$  is recommended

between the navigation channel and the basin. The impact of the presence of a bridge near the basin on visibility should therefore be considered.

Fig. 15. Turning manoeuvres in the small trapezoidal basin (a), the small trapezoidal basin optimized n°1 on one bank (b) and the small trapezoidal basin optimized n°2 on two banks (c).



## 5 Stepwise approach for optimized design of ship turning basins

The possibility of optimizing turning basin geometries varies significantly depending on the available area and the hydro-meteorological conditions. The simulations which have been carried out in this study and which have been described in the previous sections, have shown that it is not possible to propose a single generic turning basin geometry with reduced dimensions that would be acceptable under all circumstances for a given waterway network.

Therefore, a stepwise approach is proposed in Fig. 16 to select an optimized turning basin geometry that allows safe turning manoeuvres according to the conditions present on the site where the turning basin is to be implanted.

In a first step, the comfort and safety dimensions of the turning area should be defined. A comfort level implies that the turn must always be relatively easy most of the time and a safety level implies that the turn must always be possible, but with less ease. For instance, for the Nord-Pas-de-Calais network, the benchmark study proposed two sets of large (more ease) and small (less ease) dimensions of turning areas based on a screening of geometrical data (Page *et al.*, 2023). The simulations confirmed that the diameters of the circular turning areas, could be set at  $1.3 \cdot L$  and  $1.2 \cdot L$  for the comfort and safety levels respectively.

The next step is to check whether one or both sides of the navigation channel can be used as turning area. If both sides of the navigation channel can be used, a circular geometry is preferred with the largest diameter possible in between the comfort and safety levels previously mentioned. If the minimum diameter is not feasible, Optimized Basin n°2 is recommended at locations without current. Optimized Basin n°1 would also be acceptable but this is not the first choice due to the complexity of the design compared to Optimized Basin n°2. This geometry is also suitable in sections with moderate current, as long as crosswind blowing from the small base of the trapezoid can be avoided, otherwise a detailed study is necessary.

When only one side of the navigation channel can be used, the large trapezoid (i.e. comfort level trapezoid) is recommended if the space available is sufficient as long as crosswind blowing from the small base of the trapezoid can be avoided otherwise a more comfortable solution which can be derived from national guidelines or best practice should be used. In the case of the Nord-Pas-de-Calais network, a turning basin already implemented in an existing area consisting of a widening of the navigation channel on one bank in the shape of half-circle was recommended. When the space available is not sufficient, Optimized Basin n°1 is recommended except at locations with current and when prevailing wind direction is a crosswind blowing from the small base of the trapezoid. In such case, a detailed study is needed (case by case).

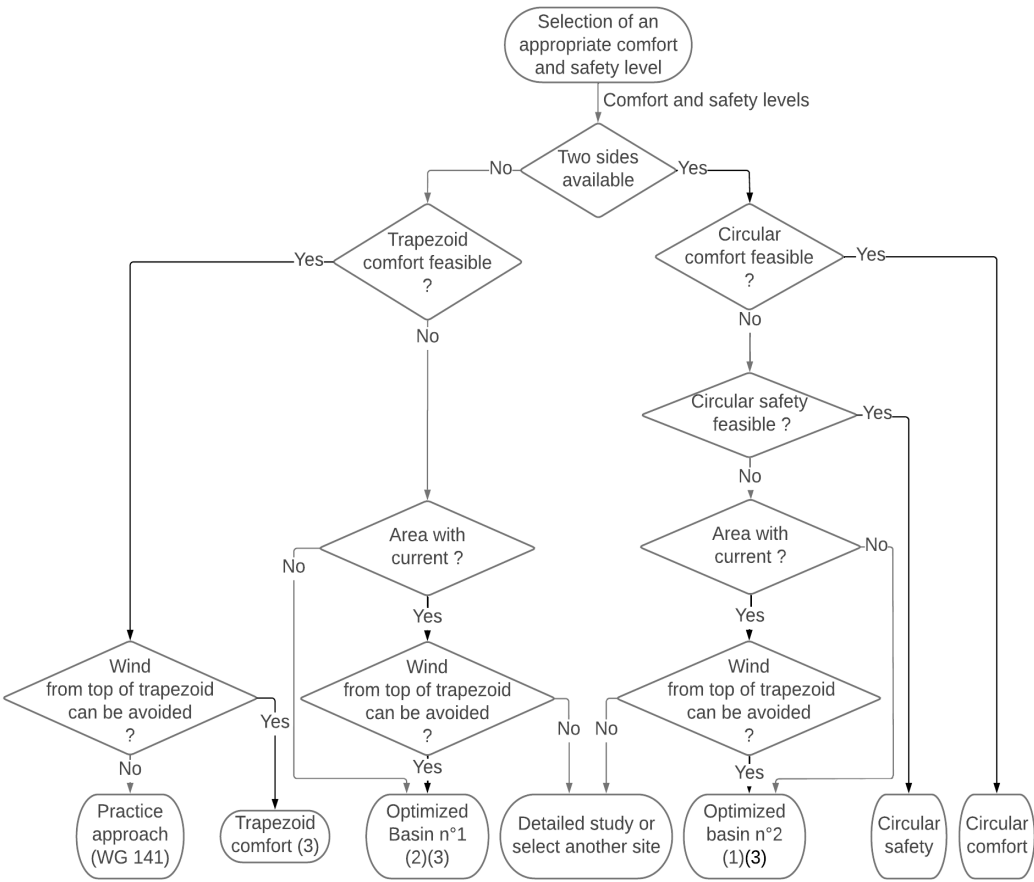
It is considered that this stepwise approach for designing turning basins reduces the amount of real time simulations that are required when upgrading a waterway network.

The methodology could be applied directly on any class Va waterway network when the guaranteed channel width is equal to 34 m, as long as the 95th percentile of the current speeds encountered at the considered location does not exceed 0.4 m/s and the 95th percentile of the wind forces does not exceed 5 Bft. For channels narrower than 34 m, the proposed geometries

are still valid but the dimensions of the trapezoid would have to be adjusted to allow ships to enter safely inside the turning basin.

The decision tree proposed in Fig. 12 is not directly applicable if currents and/or wind speeds larger than the ones tested are common on the waterway network under consideration or if none of the solutions proposed are acceptable from a construction point of view (e.g. due to environmental and/or economic constraints). In that case detailed design is required to fine-tune the proposed geometries or another construction site should be found.

Fig. 16. Decision tree proposed for waterways with current velocities  $\leq 0.4$  m/s and wind forces  $\leq 5$  Bft



- (1) Turning is not possible for a fully loaded vessel on the reaches with current and with a wind of 5 Bft
- (2) Turning is not possible for a fully loaded vessel of 135 m (Va+) on the sections with current and with a wind of 5 Bft
- (3) A clear line of sight of 3·L is recommended between the navigation channel and the basin.  
The impact of the presence of a bridge near the basin on visibility should therefore be considered.

## **6 Conclusions and recommendations for further research**

Turning manoeuvres were studied for ECMT class Va (110 m x 11.40 m) and class Va+ (135 m x 11.40 m) inland container ships (2 layers) on a real time manoeuvring simulator in circular and trapezoid turning basins of different size (comfort and safety level). The analysis of the simulations was carried out in three stages.

In a first stage, the effect of two different loading conditions (drafts 1.7 m and 2.5 m) and different hydro-meteorological conditions (wind and current) was analysed in order to identify the most critical navigation conditions. The results of simulations confirmed that circular geometries allow turning manoeuvres in any conditions and can be dimensioned according to the available space for construction between a comfort level and a safety level (which were set at  $1.3 \cdot L$  and  $1.2 \cdot L$  respectively). These simulations also showed that optimization of the initial trapezoid basins was required.

In a second stage, optimizations of the trapezoid turning basins were derived from an overlay of the simulation trajectories obtained in the first stage simulations. This resulted in two optimized designs replacing the original ones, depending on whether one or both sides of the channel can be used for construction.

In a third stage, simulations were carried out in the optimized designs and the limits for each design were established.

Finally, a stepwise approach for designing turning basins was proposed, which reduces the amount of real time simulations that are required when upgrading a waterway network. A flowchart was provided to facilitate the selection of an optimized design according to the local characteristics of the basin location. The flowchart prioritizes circular designs and comfort level solutions. When the required space for the implementation of such designs is not available, optimized solutions are proposed. When none of the proposed designs are appropriate, practice

approach (PIANC, 2019) or detailed design should be carried out to fine-tune the proposed geometries on a case by case basis.

The limitations of the optimized designs have been reached in the most extreme hydro-meteorological conditions tested (wind blowing from a top of a trapezoid in current condition) and suggest that the required area to execute turning manoeuvres in rivers with higher current and/or larger wind forces can become important and will have a significant economic and environmental impact. Moreover, with the development of autonomous navigation, further research could also be interesting to evaluate the accessibility level of an autonomous ship in the turning basins proposed in this paper.

## **7 Data Availability Statement**

Mathematical manoeuvring models are proprietary of Flanders Hydraulics and post-processing codes generated during the study are proprietary of Flanders Hydraulics and Ghent University. Simulation data and results are confidential and may only be provided upon specific request and with some restrictions to be discussed with the client.

## **8 Acknowledgments**

This study was commissioned by Voies navigables de France (VNF). The simulation studies carried out to develop optimized geometries of turning basins on the Nord-Pas-de-Calais Class V network were financed within the frame of the Seine-Escaut project (MIE co-financing).

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## 10 Tables

Table 1. Dimensions of the concept geometries.

Shape	Circular		Trapezoidal	
	small	large	small	large
Size				
Dimensions	D = 162 m (1.2 L)	D = 175.5 m (1.3 L)	135 m from the channel axis, 30 m from the top (Va+)	149 m from the channel axis, 30 m from the top (Va+)
	D = 132 m (1.2 L)	D = 143 m (1.3 L)	110 m from the channel axis, 30 m from the top (Va)	121 m from the channel axis, 30 m from the top (Va)
Channel width	34 m	34 m	34 m	34 m
Water depth (inside channel)	3.5 m	3.5 m	3.5 m	3.5 m
Water depth (outside channel)	3.0 m	3.5 m	3.0 m	3.5 m
Base angle	-	-	50°	45°

Table 2. Particulars of the design vessels for two loading conditions.

ECM T class	Transport	Loading condition	Length overall (m)	Breadth (m)	Draft (m)	Air draft (m)	Main engine (hp)	Bow thruster (hp)	Tonnage <sup>a</sup> [ton]	TEU <sup>a</sup>
Va	Containers (2 layers)	Fully loaded / empty	110	11.40	2.5 /	3.95 /	180	650	1500	104
					1.7	4.75	0			
Va +	Containers (2 layers)	Fully loaded / empty	135	11.40	2.5 /	3.95 /	255	650	2300	136
					1.7	4.75	0			

<sup>a</sup> based on (PIANC, 2020).

Table 3. Evaluation criteria.

Accessibility level	Distance banks (m)	Reserve main propeller	Reserve bow thruster	Rudder angles variations (°/s)
Inacceptable	0 m - 1 m	< 10%	< 10 %	> 4°/s
Acceptable	1 m - 3 m	10 % - 40 %	10 % - 30 %	2°/s - 4°/s
No constraints	> 3 m	> 40 %	30% - 100%	< 2°/s

Table 4. Selected simulation results - first stage.

Basin	Ship	Current direction	Wind	Draft	Manoeuvre Duration (min)	Distance banks (m)	Reserve main propeller	Reserve bow thruster	Rudder angle variations (deg/s)	Accessibility level
Circular (small)	110 m	Downstream	No	1.7	7.9	1.3	59%	51%	2.00	Acceptable
Circular (small)	135 m	Downstream	No	1.7	10.2	1.6	52%	21%	1.19	Acceptable

Basin	Ship	Current direction	Wind	Draft	Manoeuvring Duration (min)	Distance banks (m)	Reserve main propeller	Reserve bow thruster	Rudder angle variations (deg/s)	Accessibility level
Trapezoid (small)	110 m	No	No	1.7	7.5	3.4	68%	47%	2.01	Acceptable
Trapezoid (small)	135 m	No	No	1.7	11.2	2.4	52%	16%	1.79	Acceptable
Trapezoid (large)	110 m	Downstream	No	2.5	10.0	1.5	63%	37%	1.41	Acceptable
Trapezoid (large)	110 m	Upstream	No	2.5	11.8	1.3	25%	24%	0.88	Acceptable
Circular (large)	110 m	No	No	1.7	7.6	5.8	69%	60%	1.31	No constraints
Circular (large)	110 m	No	No	2.5	9.3	4.2	40%	51%	1.89	Acceptable
Circular (small)	110 m	No	5 Bft	1.7	6.4	0.1	57%	36%	2.45	Inacceptable
Circular (small)	110 m	No	5 Bft	2.5	8.1	2.3	47%	45%	1.44	Acceptable
Trapezoid (small)	110 m	No	5 Bft	1.7	9.2	2.3	53%	36%	2.17	Acceptable
Trapezoid (small)	110 m	No	5 Bft	2.5	12.5	0.0	42%	32%	1.07	Inacceptable

## 11 Figure caption list

Fig. 1. Seine-Scheldt project and the Northern part of the French inland waterway network (black frame) (source: <https://www.seine-scheldt.eu/>).

Fig. 2. Example of ECMT Va inland ship with 2 layers of containers.

Fig. 3. Heights ship models: measured from the keel to the top of the second layer of containers (right) and measured from the keel and the top of the wheel house (left).

Fig. 4. Class Va ship model (left) and class Va+ ship model (right).

Fig. 5a. Large version of the circular turning basin for the class Va. The area outside the channel is hatched and measured in hectare (ha).

Fig. 5b. Small version of the circular turning basin for the class Va. The area outside the channel is hatched and measured in hectare (ha).

Fig. 6a. Large version of the trapezoidal turning basin for the class Va. The area outside the channel is hatched and measured in hectare (ha).

Fig. 6b. Small version of the trapezoidal turning basin for the class Va. The area outside the channel is hatched and measured in hectare (ha).

Fig. 17. Manoeuvring simulator for inland navigation (Flanders Hydraulics Research, Belgium).

Fig. 18. Current field as implemented in the simulator (no current flow outside the channel).

Fig. 9. Turning manoeuvre simulated in confined turning areas with no wind and no current (small circular basin ( $\varnothing 1.2L$ ) (a), large trapezoid (b), small trapezoid (c) ).

Fig. 10. Turning manoeuvre of a class Va simulated in a small trapezoidal turning basin with no wind and no current. Pivot point in red.

Fig. 19. Overlay of turning manoeuvres trajectories obtained with a class Va vessel in a small trapezoidal turning basin.

Fig. 12. Drawing of Optimized Basin n°1 for a class Va which is proposed if a turning basin can only be put on one side of the channel (distance in m).

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Fig. 16. Decision tree proposed for waterways with current velocities  $\leq 0.4$  m/s and wind forces  $\leq 5$  Bft