Development Options for A&R Shipyard Harbour

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Master Thesis

presented in partial fulfilment
of the requirements for the double degree:
“Advanced Master in Naval Architecture” conferred by University of Liège
"Master of Sciences in Applied Mechanics, specialization in Hydrodynamics, Energetics and Propulsion” conferred by École Centrale de Nantes

developed at University of Rostock
in the framework of the

“EMSHIP”
Erasmus Mundus Master Course
in “Integrated Advanced Ship Design”

EMJMD 159652 – Grant Agreement 2015-1687

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Reviewer: Prof. Robert Bronsart, University of Rostock

Rostock, February 2018

ABSTRACT

The aim of this master thesis is to investigate based on multi-criteria analysis different layout options for Abeking and Rasmussen (A&R) shipyard harbour in terms of having constant water level and better manoeuvrability possibilities for conducting more safely and time efficiently launching operations of big vessels by barge (or floating dock) or syncrolift. After having the best layouts as a result of the analysis a more detailed design with necessary calculations was performed. At the end, cost estimation and comparison of the final layouts was carried out.

Keywords: Abeking & Rasmussen (A&R)**,** river Weser, sedimentation, navigation, harbour, shared harbour, multi-criteria analysis, layout, harbour entrance, sheet pile cofferdam, floating door, caisson, cost estimation.

DECLARATION OF AUTHORSHIP

I declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

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I have acknowledged all main sources of help.

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This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma.

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ACKNOWLEDGEMENTS

Firstly I would like to express my sincere gratitude to my internship supervisor Mr. Alexander Skalicky from Abeking & Rasmussen and university supervisor Professor Philippe Rigo from the University of Liège who supported me with their professional advice through the whole process of developing this master thesis. Without their help, it would not have been possible.

Besides my supervisors, I would like to dedicate special thanks to the Captain Mr. Edward Pietschik from Abeking & Rasmussen, for the long discussions and valuable insights about the navigation of vessels, water currents and river Weser, shared harbour and about life itself.

Furthermore, special thanks to Mr. Karsten Fach from Abeking & Rasmussen, who gave me the opportunity in the first place to join the staff of A&R for the amazing 4 months internship period. It was a great experience to witness with your own eyes how a world-class shipyard functions and the superyachts being built.

In addition, my special gratitude to a Belgian Naval & Transport company DN&T S.A and especially Mr. Adrian Constantinescus for his advice and help with the floating door design.

Moreover, great gratitude goes to my companion Raili Sepri who encouraged and supported me throughout the EMSHIP program. She made the 18-month adventure even more interesting.

Finally, I would like to thank my parents who supported me during the whole process.

This thesis was developed in the frame of the European Master Course in “Integrated Advanced Ship Design” named “EMSHIP” for “European Education in Advanced Ship Design”, Ref.:159652-1-2009-1-BE-ERA MUNDUS-EMMC.

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1. INTRODUCTION

1.1. General

The concept of the shipyard layout plays a very important role in the shipbuilding industry. In terms of material flow, easy accessibility of technical equipment it is a vital point in order to have a good efficiency and speed for keeping up with today´s high demands. Furthermore, not only the layout needs to be good in terms of material flow, but also the harbour where the ships are docked for maintenance or the new ships launched need to have certain characteristics in order to assure certain quality and safety during docking or launching operations.

The ships, especially superyachts have a tendency to get longer, wider and more complex in terms of design, building and technology used. For this reason, the shipyards need to keep renewing and modernizing themselves in order to keep up with the client´s expectations. As the ships grow in size their launching, docking and manoeuvre operations get more and more complex. Therefore, there is a demand every now and then to renew the launching mechanism, harbours, harbour basins and dredge the fairways.

As building superyachts is now one of the main branches of Abeking and Rasmussen (hereafter A&R) the company is facing and surely will face in the future a problem with launching bigger and bigger vessels. In consequence of that, this master thesis focuses on the small craft harbour that A&R uses to launch their vessels and gives new layout proposals for the harbour in order to launch better bigger vessels, have better manoeuvrability and water level unaffected from the river Weser tides inside the harbour basin. In order to understand the situation of the harbour and the area where A&R is located, first the local, as well as the current situation of the shipyard, is mapped and then the main problems are identified that are faced with the current layout solution. Secondly, a literature-based research on the sedimentation flow of the lower Weser region was done for identifying how much sedimentation comes into the harbour of the total freshwater runoff measured at the gauge of Intschede. Thirdly, a multi-criteria analysis (MCA) was performed in order to identify the best layout solutions. Last but not least a preliminary design and calculations of the proposed sheet-pile wall and entrance gate was conducted. In the end, a cost estimation of the top scored layouts was done.

1.2. A&R Location

Abeking & Rasmussen is situated on the left bank of river Lower Weser. Lower Weser is defined as the distance from Bremen to Bremerhaven. The shipyard is around 17 km from the city centre of Bremen and 53 km from Bremerhaven. Bremerhaven is a port located at the mouth of the river Weser and is one of the most important Container terminals in the world. On Figure 1 can be seen the location of A&R.

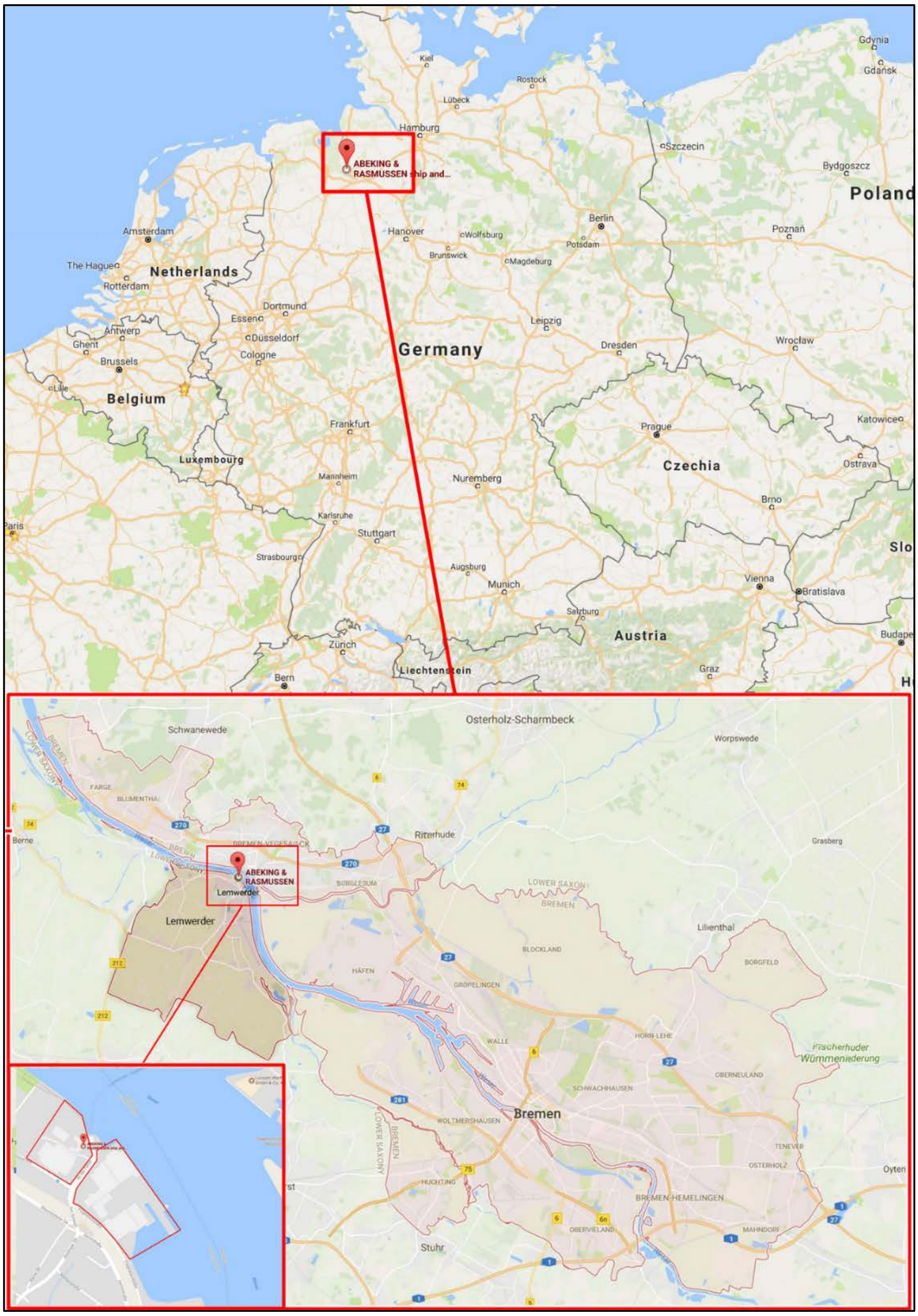

Figure 1: A&R Location on the Map

1.3. Development of the Shipyard and Shared Harbour over Time

The company Abeking & Rasmussen is family owned and has approximately 500 employees. The company was founded in 1907 by yacht builders Georg Abeking and Henry Rasmussen in Lemwerder, Germany. Quite soon, in the beginning of 1920s G. Abeking left the company and was then led only by H. Rasmussen. In 1959 H. Rasmussen inherited the company to his grandchild Herman Schaedla who was from the USA. In 1987 Herman Schaedla´s son Hans M. Schaedla joined the company. [1]

Since the establishment in 1907 on the river Weser, the company A&R has grown into a large complex, that has five halls for ships and yachts up to 120m in length, modern office buildings and a synchro lift (syncrolift is a boat and ship lifting system that lifts the vessels out of water in order to conduct maintenance work or repair). From Figure 2 can be seen an air photo of A&R territory.

Figure 2: Air Photo of A&R Shipyard.

(http://www.superyachttimes.com/yacht-news/abeking-rasmussen-a-lifetime-in-lemwerder/)

Since its establishment, the firm has built more than 6500 sailing yachts, motor yachts and mega-yachts. The yachts built in A&R generally start at a minimum of 98 feet (~30m) in length. They are the market leaders in SWATH (small waterplane area twin hull) constructions. A&R is one of the longest standing shipbuilders in the maritime industry, with over 100 years of experience behind them.

During its long history, the shipyard has faced many difficulties. It has survived inflations, fires and two world wars. That is one of the reasons, why the shipyard has grown and changed a lot, the second aspect is to have the capability to build bigger vessels. On Figure 3 can be seen the development of the shipyard and the shared harbour over time.

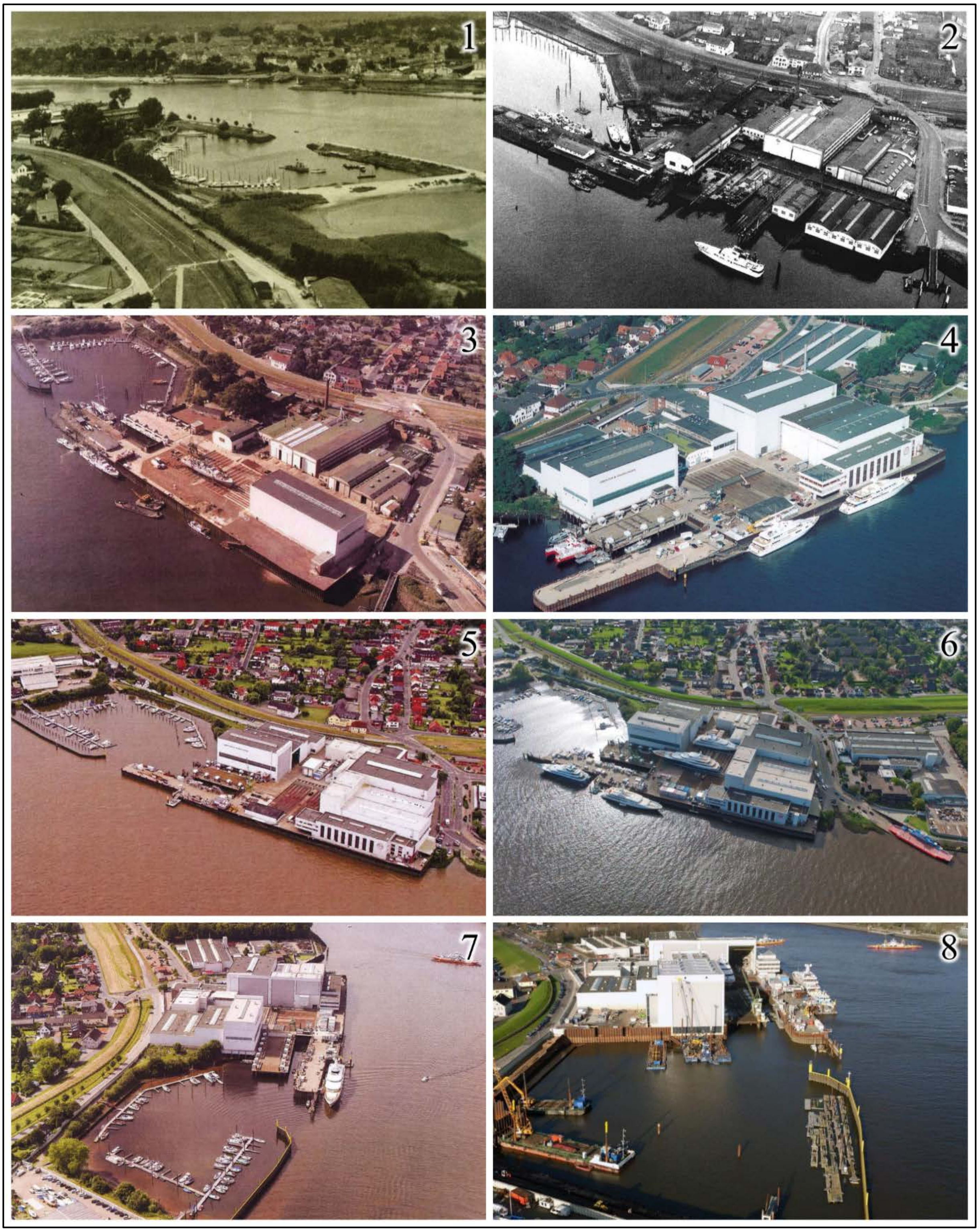

Figure 3: Development of A&R Shipyard over Time (Pictures available: A&R private collection)

1.4. A&R Shipyard and its Shared Harbour

Abeking and Rasmussen share the harbour, where they launch their ships, with the local Weser Yacht Club Bremen. The yacht club has to dismantle the floating marina and remove all the boats in the harbour in order for A&R to conduct safely docking or launching operations of vessels over 83m length. On the other hand, A&R is liable not to launch vessels that big during navigational seasons. The navigational season starts on river Weser in the beginning of April and lasts until the end of October. This kind of political situation is quite demanding for both sides, and therefore there has risen a necessity to remodel the harbour. On Figure 4 can be seen the layout of A&R shipyard which will be also the main thing studied within this thesis.

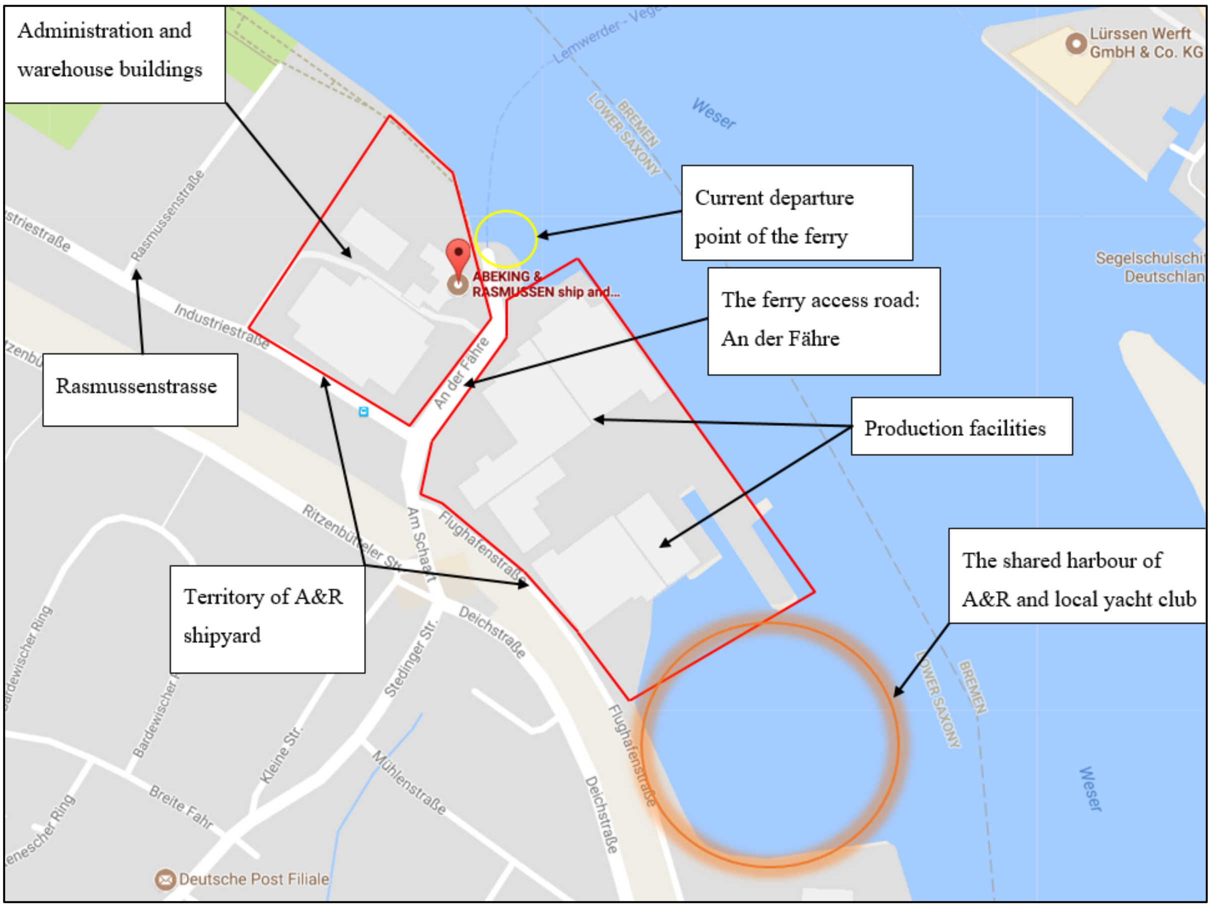

Figure 4: Layout Description of A&R Shipyard

As for now, usually the yachts built in A&R are smaller than 83m and the launching operations can be done with the syncrolift, but as the yachts have a tendency to grow in size, in the future it will become a serious problem for A&R as well as the yacht club. Vessels with a length of

83m or more are launched by barge. The first example of this is the launch of 98.4m long and 17.24m wide Aviva in January 2017 (Figure 5).

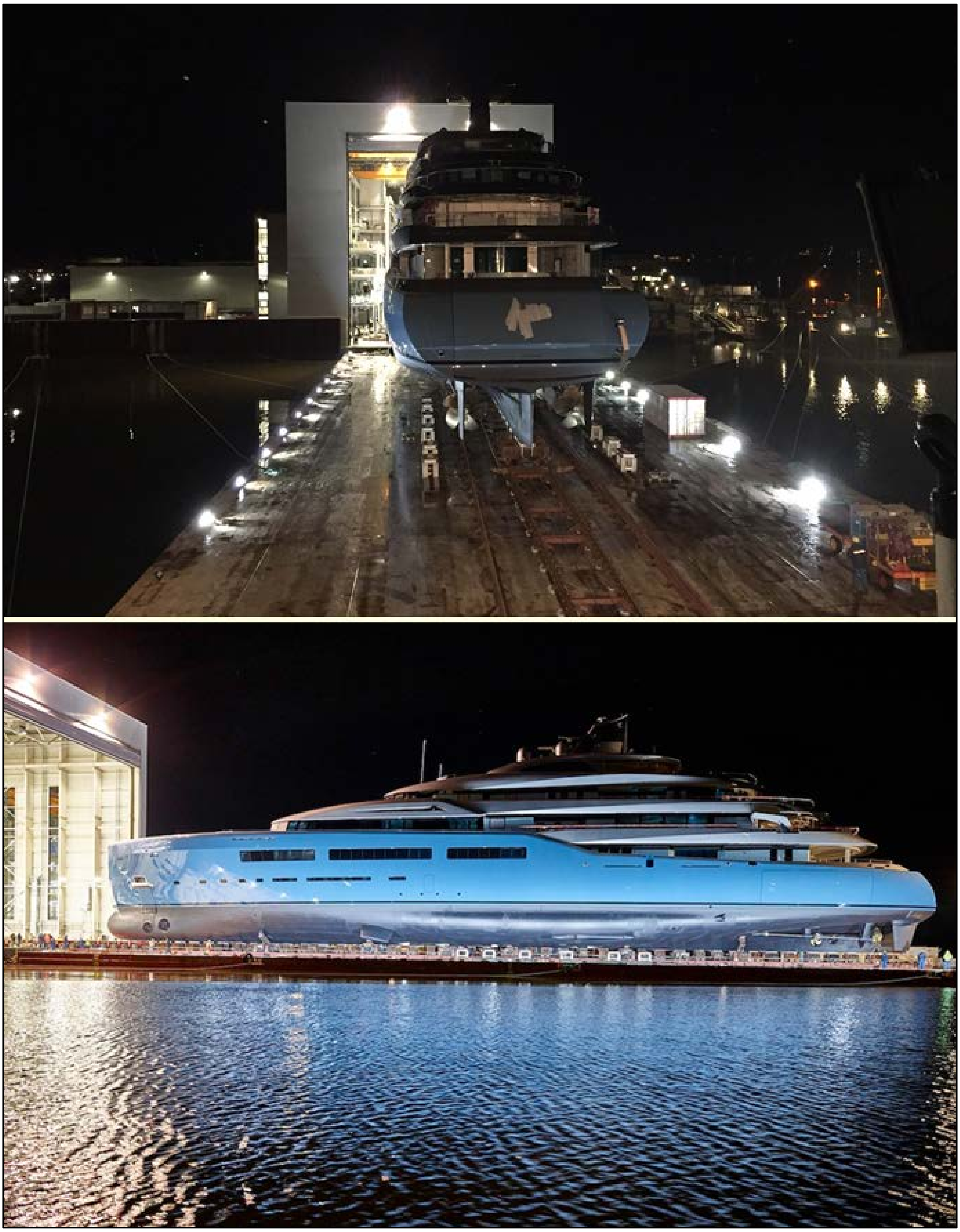

Figure 5: Launch of Aviva in January 2017 (http://robbreport.com/motors/marine/gallery/abeking-rasmussen-launches-its-largest-yacht-the-321-foot-aviva-252211/#!2/aviva-by-abeking-rasmussen-2)

2. CURRENT SITUATION OF THE SHIPYARD

2.1. Need of Changes

The local Lemwerder harbour has existed side by side with Abeking & Rasmussen over more than 100 years. However, as time passes by, the vessels built by A&R need to have more and more space in the harbour basin. That is why there is a need to modify the current layout of the harbour and rethink the location of the harbour entrance and marina layout in the basin.

Up until 2017, there has not been big challenges with launching newly built ships, as A&R has their own syncrolift for launching vessels with length until 83m. Nonetheless, as vessels, especially superyacht tend to grow in size, it was meant to be changed. In January 2017 a superyacht almost 100m in length, now known as Aviva, was launched. However, it was not launched by regular methods, but by using a Boabarge 36 (Figure 6).

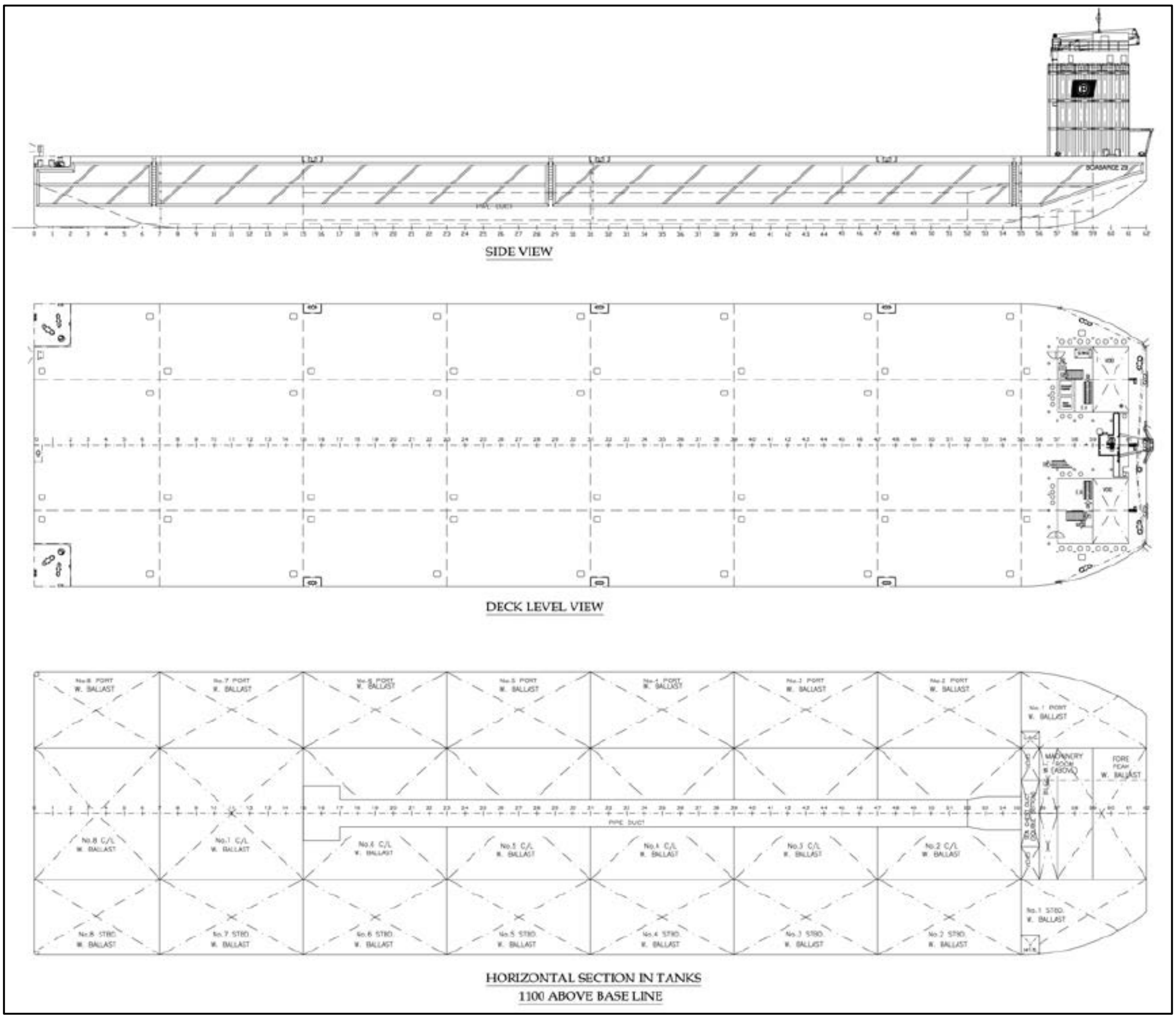

Figure 6: Boabarge 36 General Arrangement (http://www.boa.no/Default.aspx?ID=68)

On the following Figure 7 can be seen the launching of the 100m superyacht by barge.

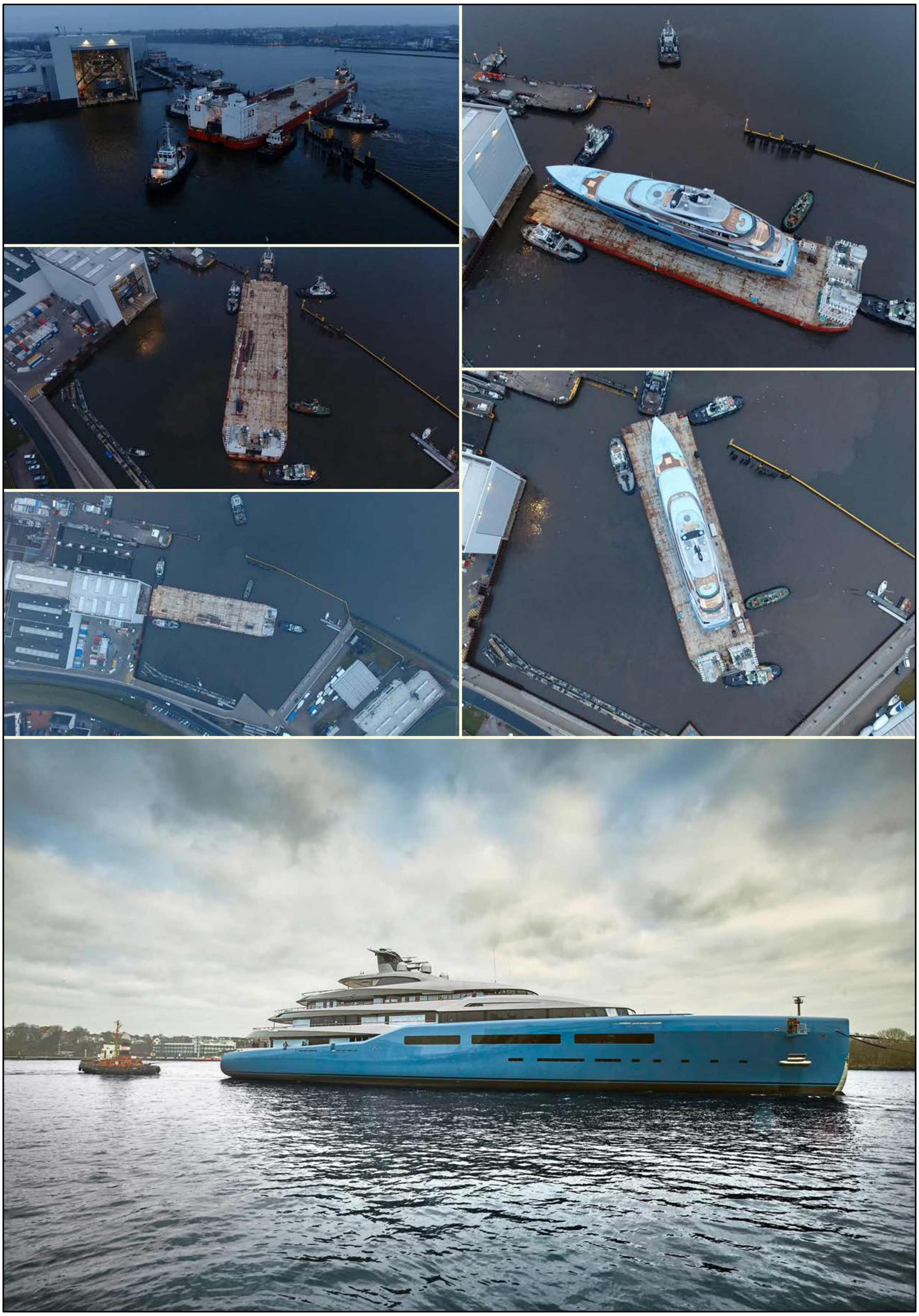

Figure 7: Launching of a Superyacht by Barge (Pictures available: A&R private collection)

As it can be seen from the above figure, the space for manoeuvring with a barge is very narrow. Furthermore, in order to enter or leave the harbour basin with the barge or with a vessel that is launched by syncrolift, turning manoeuvres of 90 degrees have to be carried out. In addition, in order to use the boabarge for the launching of the yacht from A&R shipyard, several modifications had to be done to the shipyard as well as to the harbour. The modifications made can be seen also in Figure 8 and they were following:

1) In order to build a superyacht that big a new hall was needed to be constructed;
2) Part of the existing sheet pile wall in the entrance of the harbour had to be removed for having enough space to manoeuvre inside the harbour with the barge and tugboats as the barge was needed to be rotated by 90 degrees in order to launch the new superyacht on it (Figure 7);
3) All of the pleasure crafts, floating marina and the piles had to be removed;
4) For the launching of the new vessel a concrete foundation on piles was constructed in the riverbed inside the harbour, where the barge would be submerged, in order to safely launch the new superyacht on it;
5) The launching of all the vessels is dependent on the river Weser tides. For safety reasons, the launching of the vessels can be done only during high water. This, however, means there is only a 1-2 hour window.

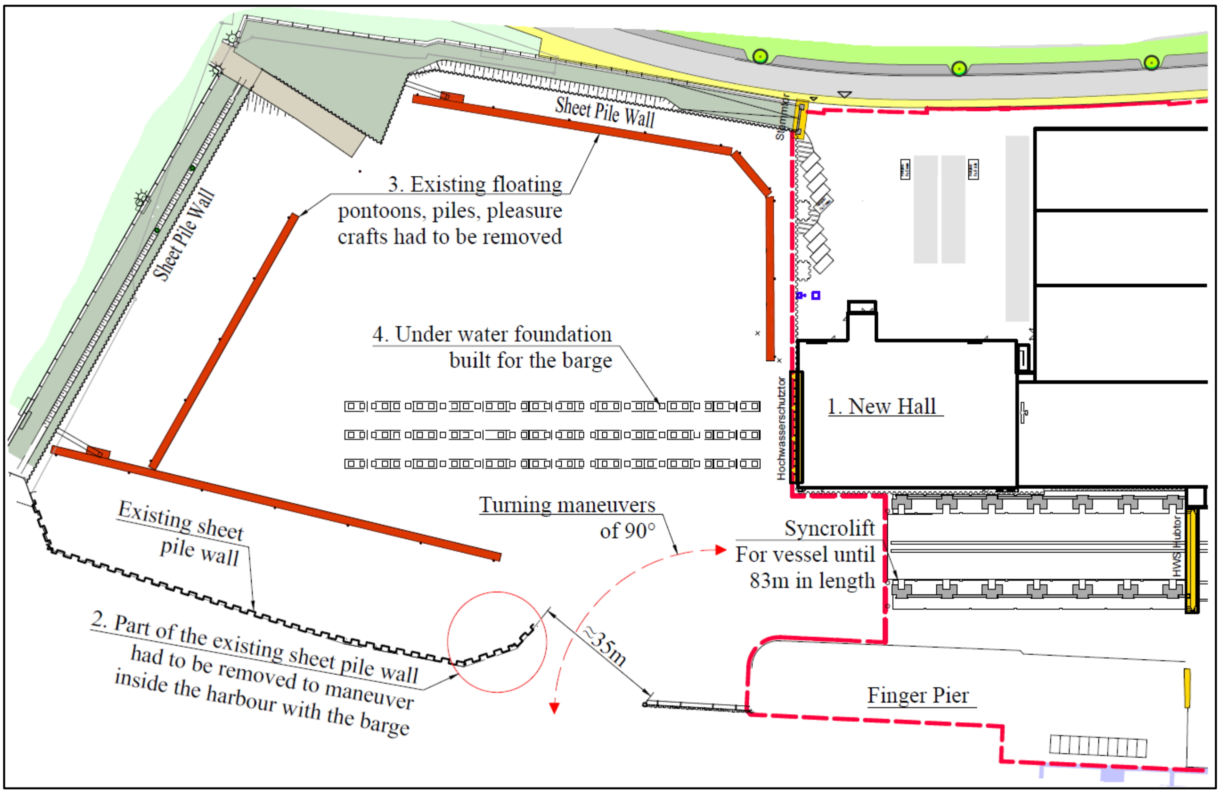

Figure 8: Description of the Current Layout

As may be observed from the above points, each point consumes a lot of time and money. However, the main problems still remain:

- There is not enough space to manoeuvre inside the harbour with big vessels and a barge, as the entrance location does not benefit it;
- The launching of the vessels depend on the river tides and the small opening (1-2h) for that depends on many factors;
- There is a permanent need to dredge the basin. (For this reason is also done the research about the river Weser sedimentation flow. However, it is only based on the available public literature data).

In order to solve the above problems and make changes to the harbour, both A&R, as well as the Local Yacht Club, need to be on the same page. This, of course, does not happen very often, as both of the sides have different perspectives and goals altogether. As presumably the local Yacht Club neither A&R will not go anywhere, the political situation for both sides is quite challenging. Nonetheless, in pursuance of to keep up with time and to develop further, both of the sides need to come once in a while to a conclusion that would benefit both.

2.2. Goals Hoped to be achieved by the Modifications

In order to solve the problems stated under paragraph 2.1 modifications to the harbour have to be made. The goal is to work out a harbour layout solution that would benefit both users, A&R and the local Yacht Club. For achieving that, the new layout should try to meet such criteria as:

- The harbour entrance should allow the entrance of the boabarge without the removal of the sheet pile wall;
- The new entrance of the harbour has to benefit in less turning manoeuvres of big vessels and the barge (such as possibly avoid the current 90 degrees turning angle);
- There should be a possibility to close the harbour for maintaining high water level (HWL) in the harbour for conducting better launching/docking operations as well as maintenance of big vessels;
- The harbour entrance(s) should benefit less sedimentation coming in;
- The reconstruction of the harbour layout has to benefit in less dredging works to be carried out in the future;

- The new layout arrangement should possibly offer more protection against floods, storms for the marina and the vessels there.
- There should be more pleasure craft places inside the harbour and the fairways should meet general guidelines for the design of marina such as given by The Yacht Harbour Association LTD (2013) [2];
- The floating marina should be relatively easy to remove in case a vessel will be launched by barge.

The points stated are quite demanding and may result in conflict as one side favours one point more as the other. To find out a suitable layout design that would satisfy both of the sides a literature-based research on the sedimentation flow in the lower Weser region (paragraph 3) was done and then a multi-criteria decision making analysis of the brainstormed layouts was performed (paragraph 4).

3. RIVER WESER

3.1. General

The river Weser is the second largest river in Germany that discharges into the southern North Sea. The rivers origin is in the confluence of the rivers Werra and Fulda at Hannoversch-Münden. The river Weser is classified as a federal waterway where a transport of goods by barges and sea-going vessels is done. Sea-going vessels can access Lower Weser ports, such as Bremen, Brake, Nordenham and Bremerhaven. On Figure 9 can be seen the general view of the Lower Weser, with the main ports and the current depths of the river. The river has an overall length of 452 km (Lange, Müller et al. (2008) [3]). The river's length downstream from the weir in the south of Bremen to the North Sea is about 120 km (Grabermann,Krause (2001) [4]).

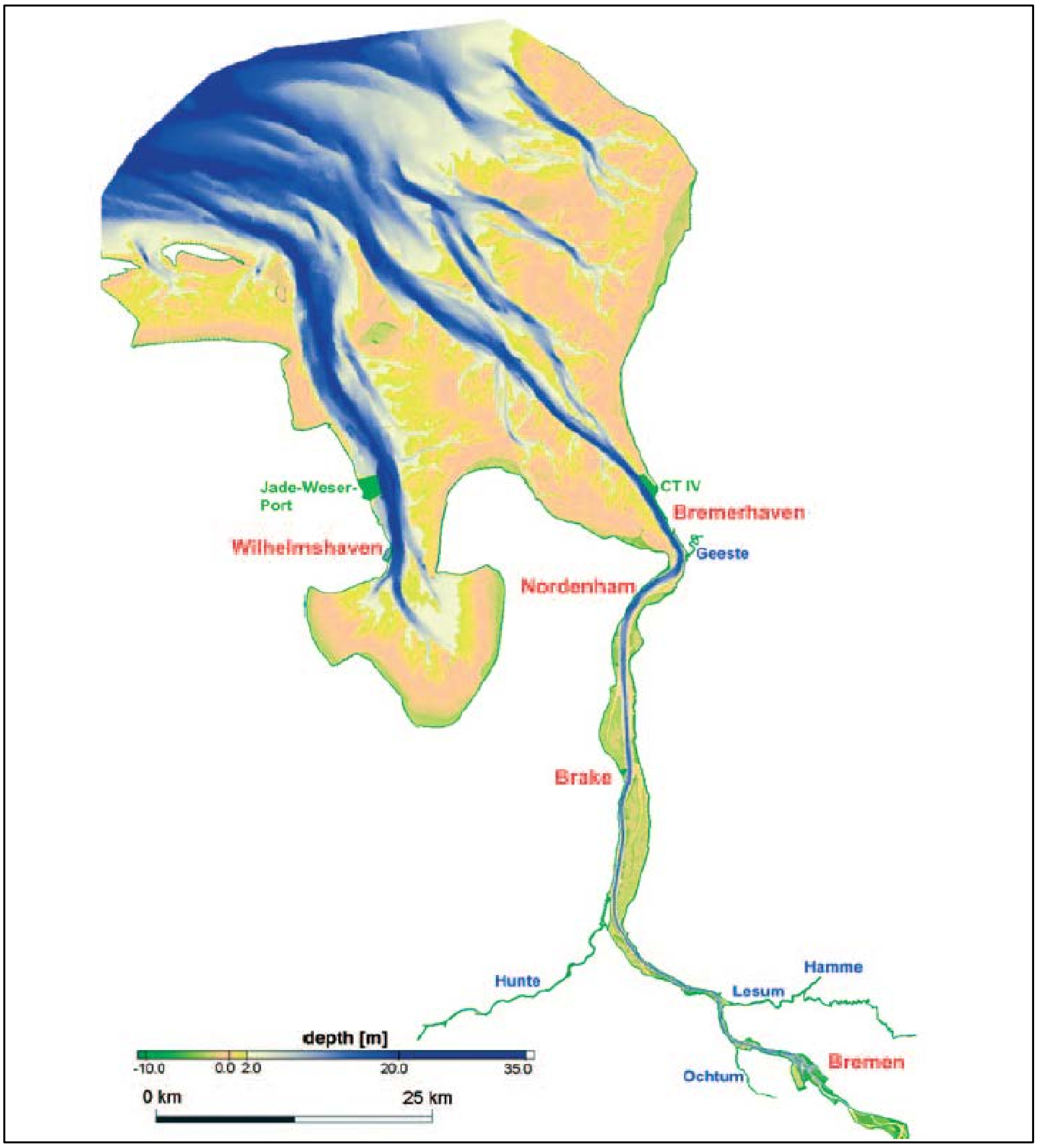

Figure 9: General Plan of the Weser Estuary [3]

Over the years, starting from 1887 there have been several corrections of the Lower Weser. The widths of the river were increased from 80m to 150-200m today and the depths from less than 5m to 9-14m today. The tidal boundaries of the river are defined by the barrage in Bremen-Hemelingen. From Table 1 can be seen the corrections works done since 1887 in Lower and Outer Weser. [3]

Table 1: Compendium of River Deepening and Correction Measures of Lower and Outer Weser [3]

1887–1895	1. Unterweser-Korrektion for vessels with 5 m draft (5 m-correction) according to a plan of Ludwig Franzius
1913–1916	Upgrading of the Lower Weser for vessels of 7.0 m draft
1921–1924	Upgrading of the Lower Weser for vessels with a draft of 7.0 m when leaving Bremen (extended 7.0 m-correction of the UW)
1922–1926	Upgrading of ‚Fedderwarder Arm' in Outer Weser to SKN – 10 m
1925–1929	Upgrading of the Lower Weser for vessels with a draft of 8.0 m
1953–1958	Upgrading of the Lower Weser for vessels with a draft of 8.7 m, levelling of the bottom sill at Brake (Braker Buckel)
1969–1971	Upgrading of the Outer Weser to a depth of SKN – 12 m (dredging works for deepening)
1973–1978	Upgrading of the Lower Weser between Brake and Bremen to SKN – 9 m
1973–1974	Deepening of the Lower Weser between Bremerhaven and Nordenham to SKN – 11m and dredging of the turning circles
1998–1999	Upgrading of the Outer Weser to SKN – 14 m

** SKN = Seekartennull = Nautical Chart Datum (During low tide the water depth is ensured e.g 9m) or also known as Charted Depth (CD).*

From Figure 10 it is possible to see the dredging works done over the years at Lower Weser for gaining a better navigational channel, the figure also points out the earlier and today´s tidal range. The tidal elevation in the Weser estuary is influenced by the distribution of the tidal wave in the North Sea and also its modification by partial reflection and shoaling effects in the estuary. Though, as a consequence, by changing the natural state of the river by various upgrading and construction measures with deeper channels and more regular cross-section that are carried out since the end of 19^{th} century, friction losses were reduced and the influence of the tide has changed drastically, thus the tidal wave coming from the North Sea can now penetrate almost till Bremen. The increase in the tidal range from the initial 20cm in Bremen grew to a range of more than 4m. The tides are semidiurnal, meaning they occur approximately every half day. [3]

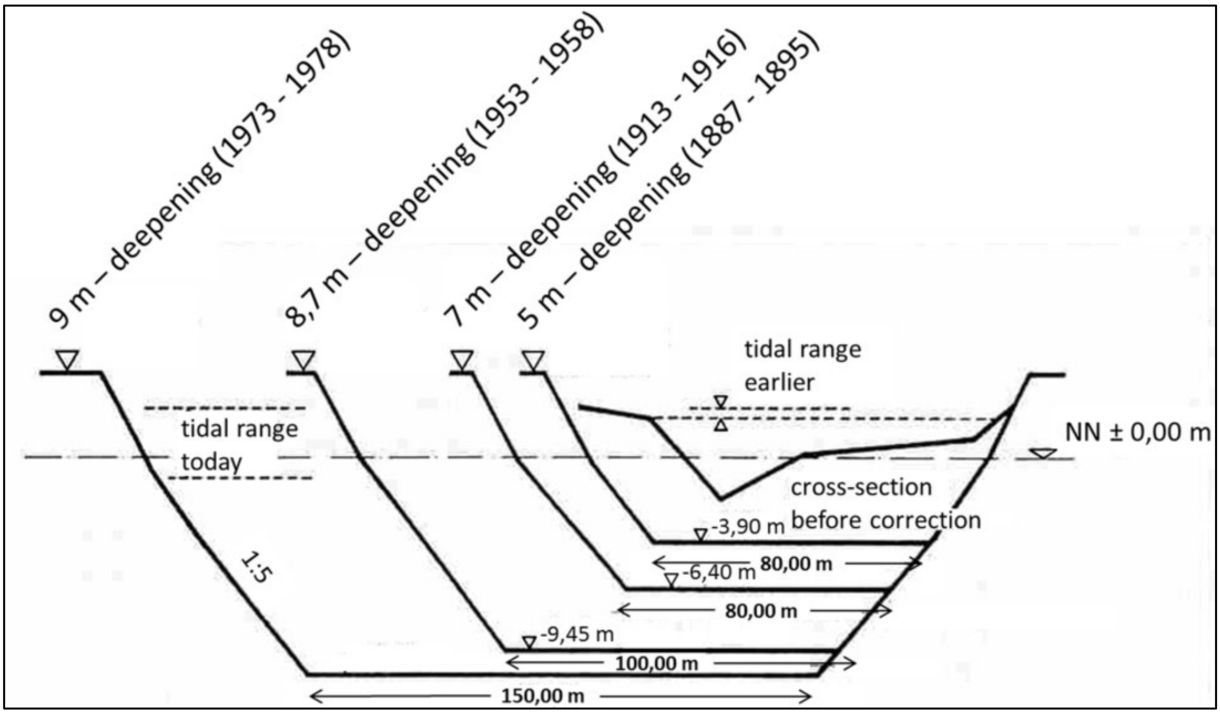

Figure 10: Dredging Works of Lower Weser over the Years
(https://www.google.de/search?q=river+weser+depth&source=lnms&tbm=isch&sa=X&ved=0ahUKEwi87rn5h9zUAhXIMBoKHbezB_EQ_AUICigB&biw=1707&bih=844&gws_rd=cr&ei=tIZoWZqzHMSiUofxl6gE#gws_rd=cr&imgrc=MbgwfpfElHYDdM:)

The tidally influenced stretch is around 120km long, extending from the weir at Bremen to the North Sea. By the use of tidal flats, it is ensured that navigation depths are 14m downstream and 9m upstream of Bremerhaven. (Becker (2011) [5])

In BIOCONSULT & NLWKN (2012) [6] is analysed the accessibility of ports in lower Weser by vessels with different draughts dependent and independent from tides. From Table 2 can be seen, that by having ensured the Charted Depth (SKN) value of 9m in the port of Bremen, vessels with a draft of 7.6m can travel there during low tide.

Table 2: Accessibility of the Ports via Tideways - Maximum Vessel Draught in m [6]

Port	**Maximum vessel draught (m) dependent on tides**	**Maximum vessel draught (m) independent from tides**
Bremen	10.70	7.60
Brake	11.90	7.90
Nordenham	13.10	10.00
Bremerhaven	14.50	12.80

From Figure 11 can be seen a representation of Charted Depth (LAT- Lowest Astronomical Tide, also referred to as SKN) for the better understanding of the actual depths in river Weser.

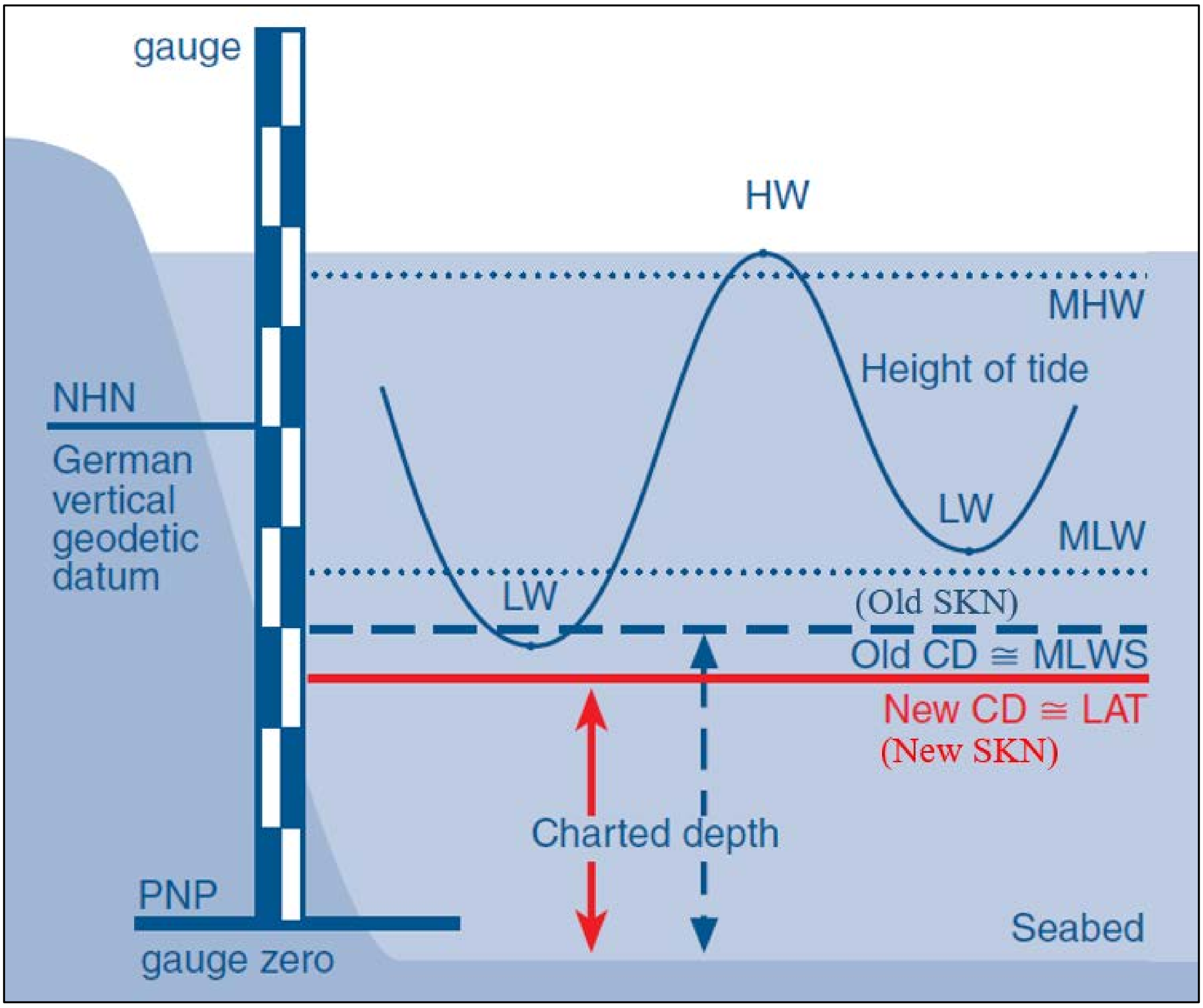

Figure 11: Charted Depth (CD)
(http://www.bsh.de/en/Products/Information_material/Chart_Sounding_Datum/Faltblatt.pdf)

Like may be observed from Table 1, the lower Weser region was upgraded in 1973-1978 to have an SKN value of 9m, meaning, with the lowest astronomical tide (LAT) the navigation depth is still remaining around 9m.

3.2. Sediments

The river bottom sediments of the Lower and Outer Weser contains mainly of medium and fine sands, with low contents of silt, clay and organic matter. However, the Middle Weser carries the gravel sediments of the lowlands [3]. Water zone with high turbidity is located between Brake and Bremerhaven (Figure 9). In the range of the centre of turbidity maximum zone (TMZ) muddy sediments dominate, containing up to 25% silt, clay and 5% organic matter, leading to an accumulation of silt and mud on the bottom of the river in that area. The turbidity maximum zone forms due to the combined effects of tidal asymmetry and non-tidal estuarine gravitational circulation. (Becker (2011) [5])

The Weser estuary is from the hydrodynamic point of view ebb-dominated, which means the ordinate tidal current acts downstream. Together the tidal pumping and the dominance of ebb tide create an interaction of cohesive and non-cohesive sediments mostly in the upstream part of the turbidity maximum zone (TMZ). The ebb-dominated tidal current has mean values around 1 m/s to 1.3 m/s, reaching a maximum value of 2.6 m/s. Even though there are a lot of constructions of sheet pilings, subaqueous embankments canalise in order to reduce sediment deposition in the navigation channel, frequent dredging is still required, especially in the turbidity maximum zone near Nordenham, where high dynamics of fluid mud is observed.

Furthermore, within one tidal cycle, the amount of fluid mud deposited and re-suspended can reach several 10s of tons. Indications are that certain amount of fluid mud consolidates and form thin layers of erosion-resistant mud, leading to the growth of river bed in some locations and thereby cause the regular need of dredging in such navigation channels. (Becker (2011) [5])

It has been documented by Nasner (1997) [7] that in the area of Bremen ports, there is a link between suspended particle matter (SPM) in the lower Weser region and the flow rate coming from the upper Weser (after the weir in Bremen, towards the land). The higher the runoffs, the higher are the suspended particle matter concentrations, which lead to higher deposit of sediments in the fairways and in the harbour basins in the lower Weser region (Nasner (1997) [7]). The SPM values can differ greatly depending on the magnitude and history of the freshwater overflow, amount of precipitation, erodible material in the flow area and on the season, however, the long-term mean SPM of the river has been measured about 40 g/m^3 and stays generally less than 50 g/m^3 (Grabermann,Krause (2001) [4]).

Freshwater runoff values measured at the gauge of Intschede, located 30 km upstream from Bremen were analysed in order to get an overview of the monthly average freshwater runoffs. Under this study, 35 years starting from 1980-2014 were studied [8]. From Figure 12 can be seen the monthly average freshwater runoff (MQ) of 35 years.

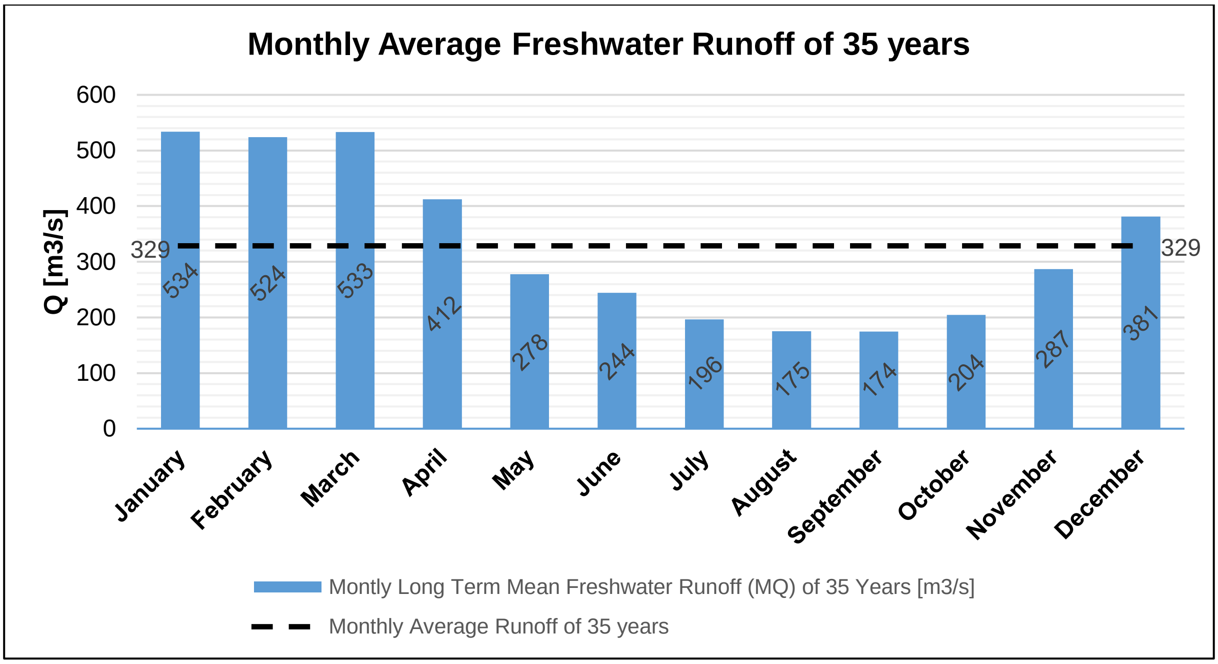

Figure 12: Monthly Average Freshwater Runoff of 35 Years

Based on the data received from Deutsches Gewässerkundliches Jahrbuch (1980-2014) [8] and considering the long-term mean SPM concentration of the river 40g/m^3 stated in Grabermann,Krause (2001) [4] and Deutsches Gewässerkundliches Jahrbuch (1980-2014) [8], the monthly average SPM volume in the freshwater discharge can be roughly estimated. The density of the solid particles was considered that of the mud 1200kg/m^3 which is in accordance to the field work done in the A&R harbour by Diplom-Geograf Dr. B. Kleefisch (2002-2012) [9]. The obtained results can be seen in Figure 13. For clarification, two colours were chosen to distinguish better the winter and navigation season. Red represents the average volume of SPM during months of the navigation season. Blue represents the average volume of SPM during months of winter season. The total average amount of SPM of 35 years per year is calculated to be around **344 352m^3/year** (this can be calculated by summing the values of all the months in Figure 13). This is the so-called "average year" based on the 35-year observation data. This value expresses the annual total amount of SPM within the annual total freshwater discharge.

The calculations were done based on the 35-year observation data collected from Deutsches Gewässerkundliches Jahrbuch (1980-2014) [8]. The values used and results achieved can be observed in APPENDIX I.

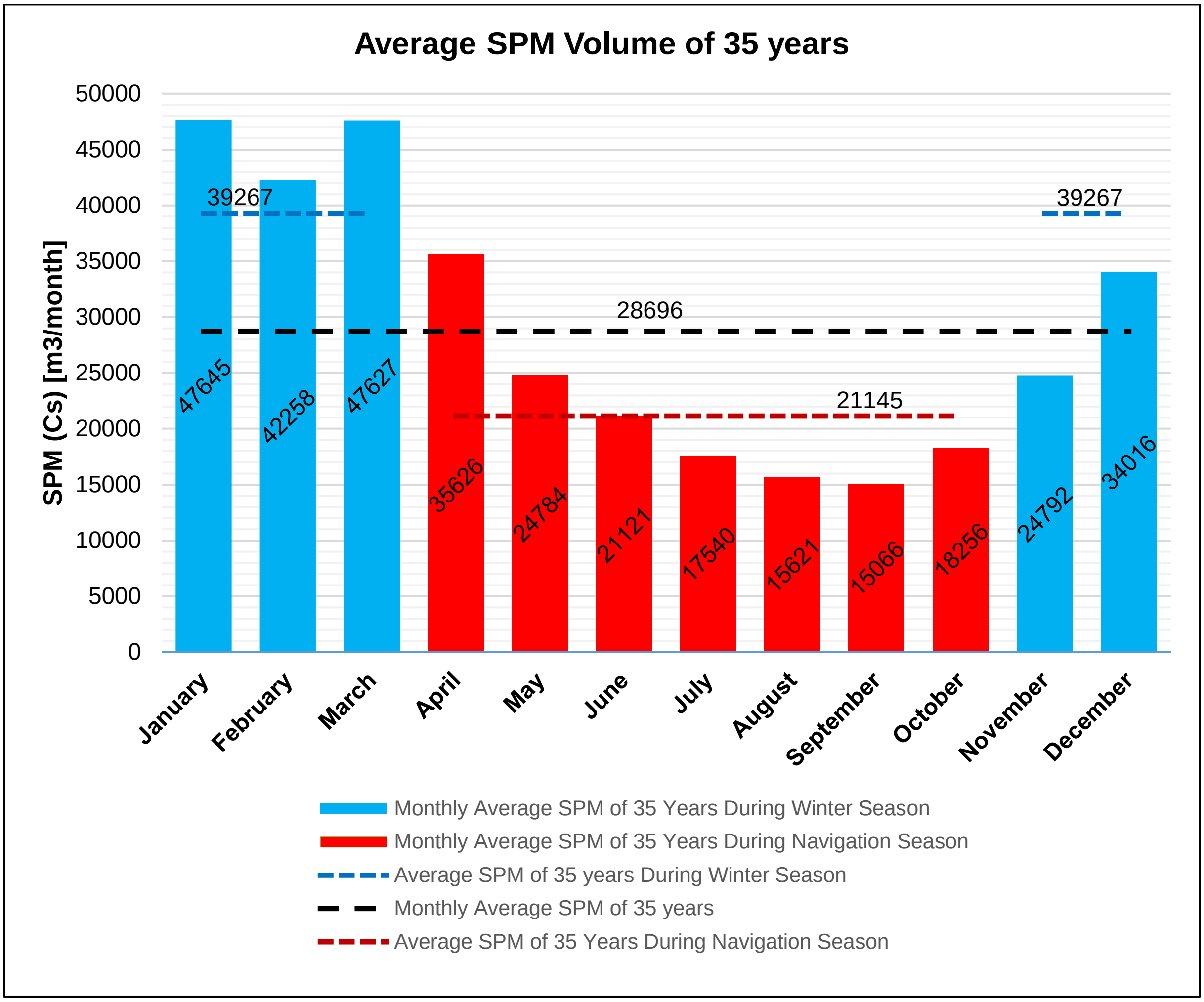

Figure 13: Monthly Average SPM Volume of 35 Years

As the seasons and years differ, the calculated amount does not show the total amount of the deposited material per year. However, it indicates to the magnitude of SPM volume in the annual freshwater discharge. Furthermore, less is known about the amount of SPM entering from the adjacent sea during flood tide, hence it is not studied under the framework of this thesis.

Figure 13 states out clearly, that during the winter season the volumes of SPM in the freshwater runoff are much higher than during navigation season. Considering the results, it would be of great benefit to close the harbour entrance with a gate(s) during the winter season for avoiding high sedimentation deposition risk into A&R harbour during that time.

Furthermore, the values obtained on the above Figure 12 and Figure 13 are in accordance with the results from Lange, Müller et al. (2008) [3], Grabermann,Krause (2001) [4] and Becker (2011) [5].

Like mentioned previously, according to Nasner (1997) [7] there is a direct link between the freshwater runoff values and the SPM concentration. This can also be observed from Figure 14, presented originally in the research of Lange, Müller et al. (2008) [3], where the magnitude of the dredging volumes in the Weser-km 0-55 lies around 300 000 m3 to 500 000m3, proving that the magnitude of the calculated average annual amount of SPM volume of 35 years per year is more or less correct.

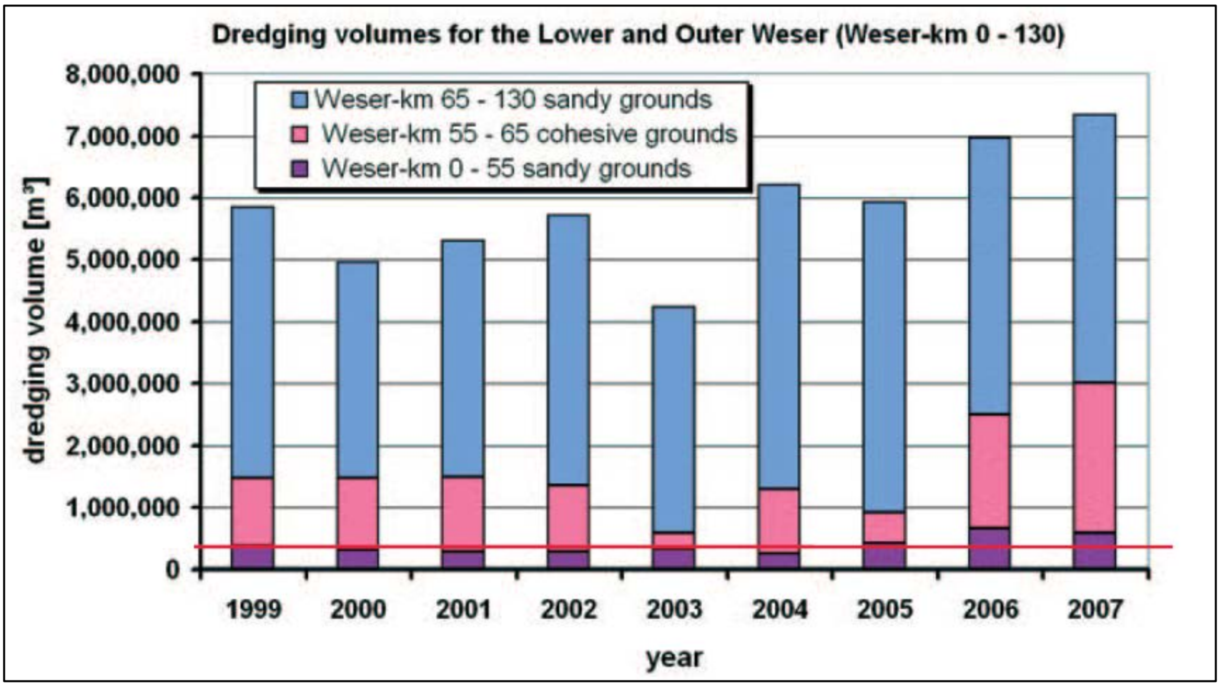

Figure 14: Dredging Volumes for the Lower and Outer Weser (Weser-km 0-130)[3]

From the following Figure 15 can be seen the monthly as well as the seasonal average SPM volume in percentage. The graph points out, that during the winter season the SPM amounts to 57% of the total annual SPM values. This is a clear indicator that during the winter season, with the higher freshwater runoff values, floods, storms etc the volumes of SPM are higher, therefore resulting also in greater deposition of sediments during that time.

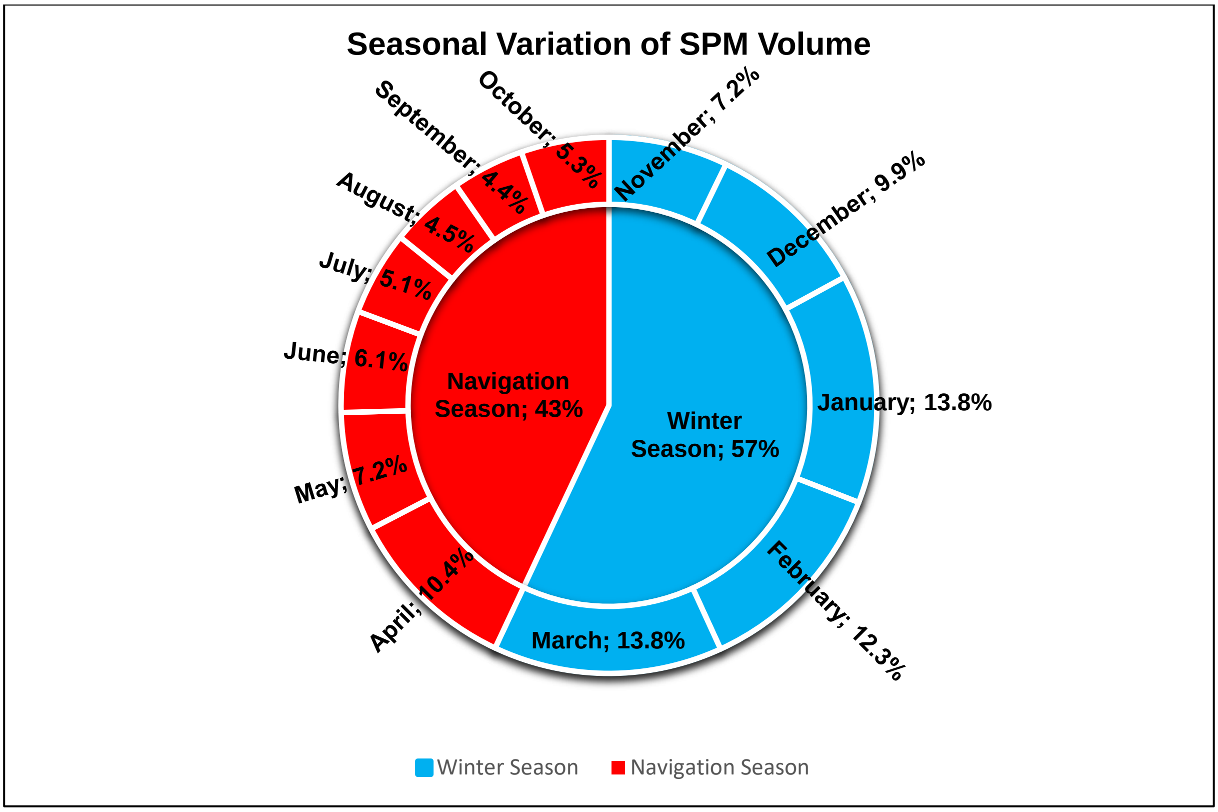

Figure 15: Seasonal Variation of SPM Volume in Percentage

It shall be noted, that it would be wise to consider also keeping the shared harbour closed during the beginning of the navigation season in April, therefore having a probability to avoid around 67% percent of the annual total deposited sediments into the shared harbour.

Of course, the amount of sediments that is deposited to A&R harbour is minor compared to the total overall transported sediments measured in the freshwater runoffs. But considering the harbour is fairly small, even low percentages deposited to the harbour from the total SPM amount may create problems and the need to dredge every now and then.

By the personal information obtained from the Lemwerder Yacht Club representative and the Captain from A&R, the amount of mud deposited into the harbour is around ~**13cm/year**. By taking the area of the harbour from a layout in Autocad ~**28 600m^2**, the total annual amount of sediments deposited into the harbour is ~**3 718m^3/year**.

After having found out previously:

1) The total average amount of SPM of 35 years per year is **344 352m^3/year**. (This value expresses the annual total amount of SPM within the annual total freshwater discharge based on the 35-year observation data).

2) The yearly total amount of sediments deposited into the shared harbour is **3 718m^3/year (~1.1%)**.

As it can be seen from the previously pointed out values, one refers to the yearly amount of sediments that are contained within the freshwater discharge and the second point states the amount of sediments that are deposited into the harbour basin every year.

Based on aforementioned values Figure 16 was created. This figure expresses, how much from the total SPM volume is deposited into the harbour **(~1.1%)** and how much elsewhere **(~98.9%)** during the average year.

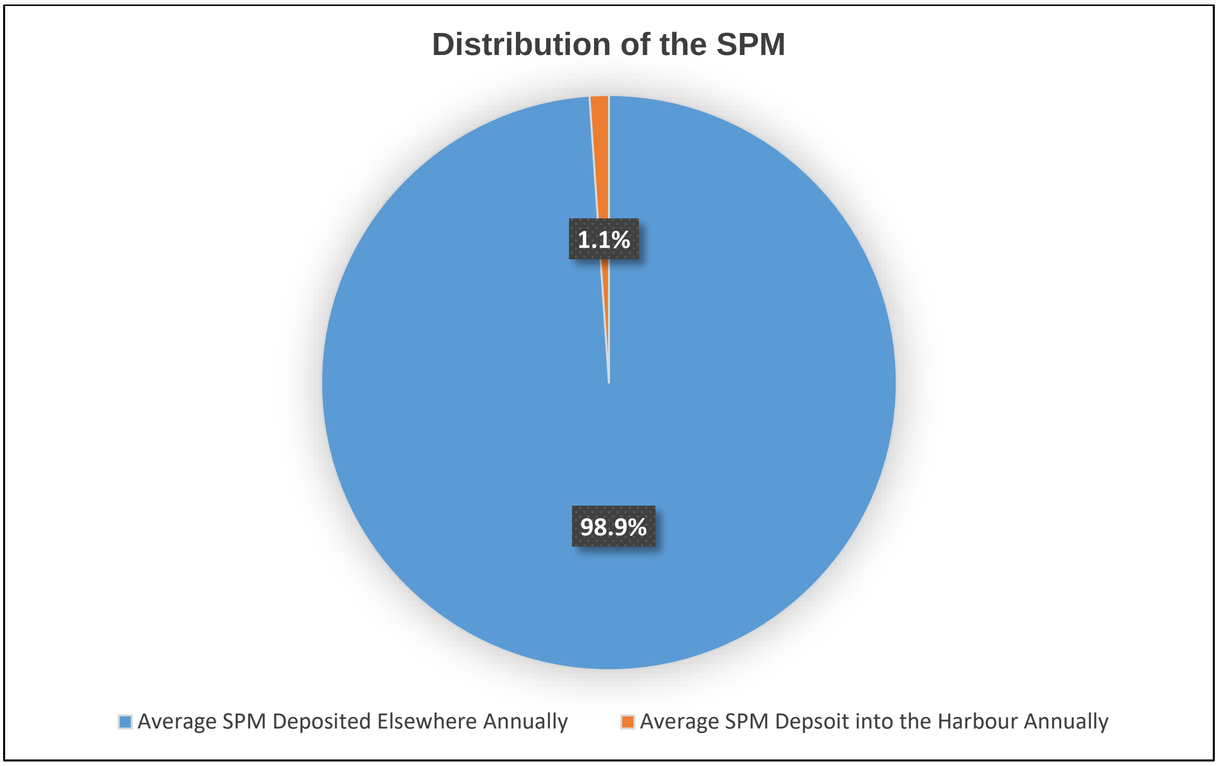

Figure 16: Distribution of the SPM

As may be observed from the above Figure 16, the average volume of SPM deposited into the harbour from the total average SPM volume is relatively low, resulting only in ~**1.1%**. The remaining **~98.9%** of sediments will be deposited somewhere else in the Lower Weser region and some of it will be transported to the North Sea. Nevertheless, as the area of the harbour is quite narrow, even very small percentage deposited create a need to dredge the harbour after every few years.

To sum up, the calculated freshwater runoff values, as well as the SPM volumes in the freshwater discharge, are all based on the 35 years observation data. Meaning, the average values obtained for months and years are not taken by the observation data of one year but from 35 years. This ensures, that the average values used are more precise and describe better the average year. Of course, there are and will be extreme cases to consider, but by using this long-term data, it gives more or less the exact results and avoids dispersion.

Furthermore, as it can be observed from Figure 15, for each month it is indicated in percentage how much is the amount of the SPM from the total average of 35 years. As it can be observed, during winter season the amount of sediments is 57%. Comparing the amount of sediments during winter season (57%) with the deposited sediments into the harbour in one year (3718m^3/year) we may approximately state, that from the SPM amount that is deposited into the basin, maximum 57% of sediments can be avoided if the harbour would be closed during winter season. Of course, this is a very rough estimation and only based on the available literature data, however, it delivers a certain magnitude of how much sediments it is possible to avoid. Thus, it gives a good reason to deliberate over the reconstruction of the harbour, as in the end, it holds benefits towards both of the parties involved.

Finally, by the information obtained by the personal communication with Prof. P. Rigo from the University of Liège, in order to determine the exact amount of sediments deposited into the harbour it would be necessary to create a hydraulic model of the currents that bring in the SPM and then compare it with the volume of water of each configuration. However, as this option would probably deliver exact results, it requires far more time and money.

4. MULTI-CRITERIA ANALYSIS OF THE HARBOUR LAYOUT

4.1. Necessity of Multi-Criteria Analysis

The multi-criteria assessment is based on the feasibility analysis of various harbour layout solution that takes into account all the stakeholders – here within this work, the assessors were the author of this thesis (K. Tull), the Captain from A&R shipyard (Mr E. Pietschik), the Head of Production department in A&R (Mr A. Skalicky) and a member of the local Lemwerder Yacht Club.

By brainstorming eight harbour layouts, each layout having at least two sub-layouts (A, B, C, D) with minor modifications separating each other from the other, were generated and improved continuously through the analysis by taking into account the various recommendation from each part participating in the multi-criteria assessment.

It shall be noted, that the layout selection is a matter of politics, economy and engineering and many other various disciplines. It could be said that it is a matter of the entire local community who live there and may or may not have other interests involved in the area of question. Sometimes the areas or the parts of interest become really big and therefore may result even in international disagreements. That is why usually the selection of proper layouts or other type of structures that involve science of engineering is performed by the engineers. However, they should take into account different interest involved and seek balance among those interest. In order to achieve balance between the sides involved a multi-criteria analysis was performed for having a harbour layout solution that would take into consideration all interests of the stakeholders. [10]

4.2. Methodology of the Analysis

The case study to find a suitable harbour layout design uses the decision support method Multi-Criteria Decision Analysis, also known as MCDA or MCA. The main purpose for using that is to offer for the decision makers a way to reach goals by identifying the most sustainable options in an organized and structured way. The basic steps can be listed as [11]:

1) Propose/ identify the alternatives;
2) Identify the decisions criteria and their indicators;
3) Weight the decision criteria’s by their relative importance;

4) Evaluate the performance of each alternative in relation to each defined criteria;
5) Calculate the results.

Points 1-3 were performed in collaboration with the stakeholders. Point 4 and 5 were done by the author of this work as he was considered as an independent party. For a more detailed overview, a flowchart of the total process was constructed (Figure 17).

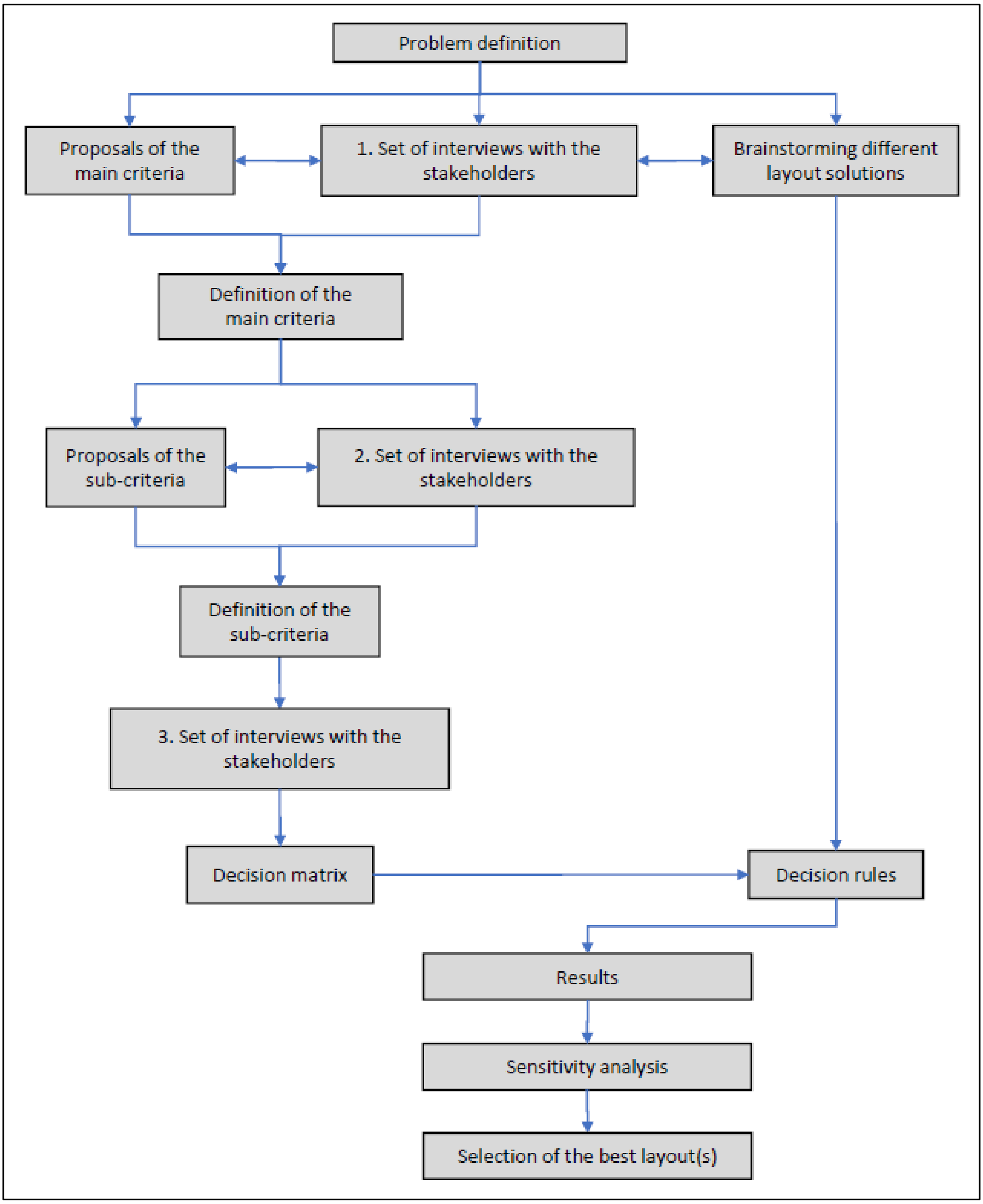

Figure 17: Flow Chart of the Multi-Criteria Analysis

From the above Figure 17 can be seen, that based on the interviews finally a decision matrix was developed and rules for the grading of the sub criteria's defined. In simple terms, now the different options (layouts) can be evaluated with respect to different criteria. This, however, means giving values to the defined matrix elements.

It was decided that the layouts will be evaluated according to quantitative assessment as the method is more precise than qualitative assessment. However, by doing that, there is a need to evaluate the layouts by their performance and to use weighting factors.

The fundamental difference between the aforementioned methodologies is that the qualitative analysis decision matrix does not contain any numerical values and therefore is more or less based on the subjective judgement of the team executing the analysis. On the other hand, the quantitative assessment decision matrix is based on numerical values by evaluating different criteria's numerically. Nonetheless, the quantitative assessment is more complicated and requires more effort by determining first how and in which units to measure the scores of each criterion and secondly how to convert the obtained different scores to the same units in order to perform a total assessment. In this study, the assessment strategy was to use performance ratings with the use of weighting factors by introducing its own measuring system that is applicable to all the criteria. [10]

The criteria's for the multi-criteria analysis are defined under section 4.3.

4.3. Defined Criteria

To perform the multi-criteria analysis first the main criteria and its sub-criteria need to be defined. The final main criteria's as also the sub-criteria's were selected based on the interviews with the stakeholders. Those are:

1) Entrance of the harbour;
    i. Width of the harbour entrance for A&R vessels;
    ii. The harbour entrance location impact on the shipping traffic;
    iii. Necessity of a secondary entrance for the marina user;
    iv. The size of the vessels that can access the harbour (for example, if a 125 m vessel can access the harbour);

2) Maneuverability inside the harbour basin;
    i. Floating marina influence on the launching of A&R vessels by barge;
    ii. Accessibility of the syncrolift (for example, if a vessel with a length of 90m can access the syncrolift);
    iii. Moving and rotation possibilities inside the harbour basin in terms of space and safety;
3) Time to release a ship;
    i. Time to launch a vessel by barge (with closed gate);
    ii. Time to launch a vessel by syncrolift (with closed gate);
4) Effect of tides/ currents/ sedimentation;
    i. Accessibility of the harbour during high or low tide during navigation season;
    ii. During navigation season, tide caused currents inside the harbour basin;
    iii. Sedimentation transport inside the harbour basin or to the entrance;
5) Impact on the marina and its users;
    i. Number of boat place;
    ii. Accessibility of floating pontoons by land and river;
    iii. Width of the fairways between floating docks and berthing places;
    iv. Accessibility of the slipway with pleasure crafts;
    v. Future possibilities for having more and/or bigger boat places (for example: min size of boats 9m);
6) Complexity of the solution and need of public authorization;
    i. Complexity of the solution;
    ii. Need of public approval in case of harbour extension into the river channel;

The criteria's were chosen to evaluate better the performance of the layout, living aside the cost criterion and by that reducing the possibility to be influenced by the cost factor. It is because usually the cheapest, neither the most expensive options does not necessarily mean the best solution in terms of safety, reliability, environmental or any other aspects.

The selection of the above criteria's was a difficult process and required several attempts of interviews with the different sides involved.

After having defined the main criteria and their corresponding sub-criteria's the grading system of the sub-criteria was established.

4.4. Performance Rating

4.4.1. Grading System

The grading system of the sub-criteria was generated considering the stakeholder's opinions and relevant importance of one sub-criteria. From Table 3 can be seen the principle of how the grading was done.

Table 3: Grading Example of Sub-criteria

Criteria	1) Width of the harbour entrance for A&R vessels;					
Entrance of the harbour	Grade	Explanation				Points equal to
	A	Excellent		≥ 50m		10
	B	Good		46…< 50m		8
	C	Satisfactory		43…< 46m		6
	D	Poor		40…< 43m		4
	E	Bad		< 40m		2
	2) The harbour entrance location impact on the shipping traffic;					
	Grade	Explanation				Points equal to
	A	No impact on traffic				10
	B	Low impact on traffic				7.5
	C	Moderate impact on traffic				5
	D	High impact on traffic				2.5
	3) Necessity of a secondary entrance for the marina user;					
	Grade	Explanation				Points equal to
	A	No need- or the location and the width of the 2nd entrance is good;				10
	B	Moderate- or the location and the width of the 2nd entrance can be better;				6.67
	C	High Need- or the location and the width of the 2nd entrance is not good and can create safety risks;				3.33

From the above Table 3 can be observed, a grade, for example from A to D was given, where the grade A represents the most perfect condition and therefore has the highest points. The grades were selected in alphabetical order, where the next alphabet has a lower value of points.

Later the given grades (for example A, B or C) were converted into their representative points. The process was implemented like that because the different sub-criteria's can be evaluated with different stages. For a precise evaluation, one sub-criteria may need only the grades from A to C, as the other one from A to E.

In order to understand how much each grade is worth the maximum number of points, which is always 10p, was divided proportionally with the number of grades, for example from A to C, meaning the grade $C = 1/3 \cdot 10p = 3.33p$, the grade $B = 2/3 \cdot 10p = 6.67p$ and the grade $A = 3/3 \cdot 10p = 10p$. This process was implemented for each sub-criteria. For the exact process, an excel spreadsheet was created and each sub-criteria of each layout graded accordingly. In APPENDIX II can be seen the system of grading the sub-criteria.

4.4.2. Weighting Factor

After having rated the sub-criteria, it is not advised to simply sum up the criteria's as their importance might not be the same. In order to achieve a reliable total score, each and every one of the main criteria's has to be assessed by their relative importance. This is done by using the weighting factors. The weighting factor (WF) represents the importance of one criterion in the analysis with respect to the total criteria's defined. Within this study a group of representatives (named in section 4.1) was asked to evaluate the previously defined 6 different main criteria with an assigned range of weighting factors from 0.00 to 1.00 (from 0% to 100%) in such a way, that the total sum of the factors would equal to 1.00 (100%). The final weighting factor of one criterion was selected the average of the total representative score.

4.5. Results of the Multi-Criteria Analysis

After having defined the decision matrix and established the rules for grading the sub-criteria, the layouts (APPENDIX II) were evaluated. In terms of achieving adequate results, the evaluation process was done only by the author of this thesis for avoiding any conflict between the two stakeholders (A&R and the Local Yacht Club). As the stakeholders have their own set of goals and preferences they could not be considered as impartial.

The results of the multi-criteria assessment (MCA) are listed in Table 4. The table indicates the weighting factors decided for each criterion as well as the representative's individual weight in percentage. Furthermore, under each main criteria can be seen also its sub-criteria's. Finally, every layout has for its main criteria a score that is the average of the sub-criteria's listed there. The final score of one layout was acquired by multiplying each criteria's weighting factor by the average score of sub-criteria's listed there and by summing all the criteria's.

Table 4: Results of Multi-Criteria Analysis

MULTI-CRITERIA ANALYSIS ON A&R SHIPYARD SHARED HARBOUR																							
Nr	**Criterion**	**Weighting factor**	**RATING of LAYOUTS [Give Points 10/10]**																				
			Layout 1 (Reference)	**Layout 2**	**Layout 3**				**Layout 4**		**Layout 5**		**Layout 6**				**Layout 7**			**Layout 8**			
					A	**B**	**C**	**D**	**A**	**B**	**A**	**B**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**A**	**B**	**C**	**D**
1	Entrance of the harbour	0.183	5.38	8.04	6.83	7.67	8.50	8.50	7.50	8.50	7.63	8.13	7.83	8.67	9.50	9.50	7.54	7.54	7.54	7.83	8.67	9.50	9.50
80.0%	*A.Skalicky*	***20.0%***	**Sub-Criteria to Consider**																				
70.0%	*E. Pietschik*	*30.0%*	*1) Width of the harbour entrance for A&R vessels;*																				
95.0%	*Weser Yacht Club*	*5.0%*	*2) The harbour entrance location impact on the shipping traffic;*																				
82.0%	*K.Tull*	***18.0%***	*3) Necessity of a secondary entrance for the marina user;* *4) The size of the vessels that can access the harbour (for example, if a 125 m vessel can access the harbour);*																				
2	Maneuverability inside the harbour basin	0.208	5.06	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.22	7.22	7.22	6.11
50.0%	*A.Skalicky*	***30.0%***	**Sub-Criteria to Consider**																				
40.0%	*E. Pietschik*	*30.0%*	*1) Floating marina influence on the launching of A&R vessels by barge;*																				
90.0%	*Weser Yacht Club*	*5.0%*	*2) Accessibility of the synchrolift (for example, if a vessel with a length of 90m can access the synchrolift);*																				
64.0%	*K.Tull*	***18.0%***	*3) Moving and rotation possibilities inside the harbour basin in terms of space and safety;*																				
3	Time to release a ship	0.120	1.50	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00
30.0%	*A.Skalicky*	***20.0%***	**Sub-Criteria to Consider**																				
35.0%	*E. Pietschik*	*5.0%*	*1) Time to launch a vessel by barge (with closed gate);*																				
80.0%	*Weser Yacht Club*	*10.0%*	*2) Time to launch a vessel by synchrolift (with closed gate);*																				
51.0%	*K.Tull*	***13.0%***																					

MULTI-CRITERIA ANALYSIS ON A&R SHIPYARD SHARED HARBOUR																							
Nr	Criterion	Weighting factor	RATING of LAYOUTS [Give Points 10/10]																				
			Layout 1 (Reference)	Layout 2	Layout 3				Layout 4		Layout 5		Layout 6				Layout 7			Layout 8			
					A	B	C	D	A	B	A	B	A	B	C	D	A	B	C	A	B	C	D
4	Effect of tides/ currents/ sedimentation	0.175	5.56	7.78	3.33	7.78	8.89	8.89	7.78	7.78	7.78	7.78	3.33	7.78	8.89	8.89	3.33	7.78	8.89	3.33	7.78	8.89	8.89
20.0%	*A.Skalicky*	***10.0%***	**Sub-Criteria to Consider**																				
5.0%	*E. Pietschik*	*30.0%*	*1) Accessibility of the harbour during high or low tide during navigation season;*																				
60.0%	*Weser Yacht Club*	*20.0%*	*2) During navigation season, tide caused currents inside the harbour basin;*																				
41.0%	*K.Tull*	***10.0%***	*3) Sedimentation transport inside the harbour basin or to the entrance;*																				
5	Impact on the marina and its users	0.190	8.93	7.93	6.87	6.87	6.87	9.00	8.13	8.13	7.93	7.93	7.07	7.07	7.07	8.80	7.93	7.93	7.93	6.87	6.87	6.87	9.00
15.0%	*A.Skalicky*	***5.0%***	**Sub-Criteria to Consider**																				
5.0%	*E. Pietschik*	*0.0%*	*1) Number of boat place;*																				
5.0%	*Weser Yacht Club*	*55.0%*	*2) Accessibility of floating pontoons by land and river;* *3) Width of the fairways between floating docks and berthing places;*																				
25.0%	*K.Tull*	***16.0%***	*4) Accessibility of the slipway with pleasure crafts;* *5) Future possibilities for having more and/or bigger boat places (for example: min size of boats 9m);*																				
6	Complexity of the solution and need of public authorisation	0.125	10.00	6.67	6.67	5.00	5.00	5.00	5.00	5.00	6.67	6.67	6.67	5.00	5.00	5.00	6.67	5.00	5.00	5.00	3.33	3.33	3.33
0.0%	*A.Skalicky*	***15.0%***	**Sub-Criteria to Consider**																				
0.0%	*E. Pietschik*	*5.0%*	*1) Complexity of the solution;*																				
0.0%	*Weser Yacht Club*	*5.0%*	*2) Need of public approval in case of harbour extension into the river channel;*																				
0.0%	*K.Tull*	***25.0%***																					
	TOTAL	**1.00**	**6.13**	**7.36**	**6.31**	**7.03**	**7.38**	**7.55**	**7.09**	**7.27**	**7.29**	**7.38**	**6.53**	**7.25**	**7.60**	**7.69**	**6.49**	**7.06**	**7.26**	**6.28**	**7.00**	**7.35**	**7.52**

From the above Table 4 can be observed, that according to the multi-criteria analysis the four best layout solutions would be:

1. Layout 6D – 7.69p
2. Layout 6C – 7.60p
3. Layout 3D – 7.55p
4. Layout 8D – 7.52p

The best-scored layouts are also indicated in Figure 18. More precise drawings of the top scored layouts can be seen in APPENDIX III.

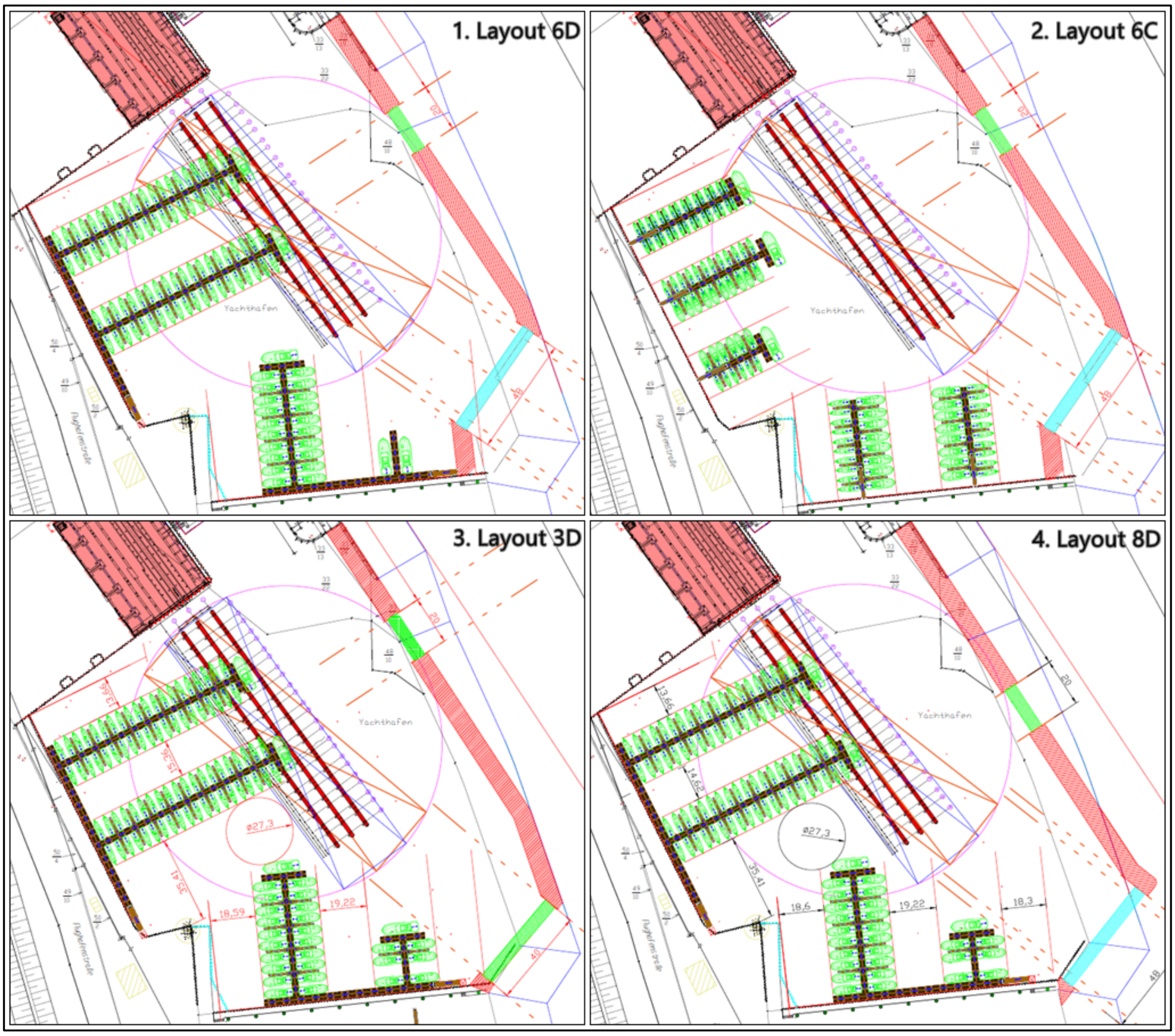

Figure 18: Top Scored Layouts

The primary difference between the four layouts is the entrance width and location, the layout of the marina, number of boats, and the complexity of the solution. All the brainstormed layouts indicated in the multi-criteria analysis can be seen in APPENDIX II.

4.6. Performance Rating – Sensitivity Analysis

As one might assume, the performance rating is rather vulnerable to arbitrary opinions of the representatives. It is without a doubt impossible to fully eliminate the arbitrariness, however, it is possible to investigate its influence on the final results. This can be done by conducting a sensitivity analysis on the defined weighting factors. The sensitivity analysis is based on assumptions that if there is a doubt with one or more criteria's importance and its weighting factor and we need to know the results when it assumes other values. In order to do that, it is assumed for a certain criteria a different weighting factor – say 0.1 – and the difference is shared proportionally between the other criteria, by that decreasing or increasing its relative importance.

In this sensitivity analysis conducted, the criteria's weighting factor were increased in order to demonstrate the impact of the criteria under consideration. All the 6 main criteria's were modified one by one. The results obtained can be seen under each criteria's respective table (Table 5-14). Furthermore, as to show the impact of each criterion under consideration, figures (Figure 19- 24) based on the top scored results of the multi-criteria analysis (MCA) were created to express a layouts change in rank with respect to the change in the weighting factor. However, as there are in total 21 layouts (APPENDIX II) participating in the multi-criteria analysis (MCA) it would be a chaos to display all of them on the figures. Hence, only the top four scored layouts (APPENDIX III) by the MCA and by the sensitivity analysis are analysed on the figures in order to avoid any sort of confusion. In addition, the scores of all the layouts can be seen in each criteria's sensitivity analysis.

Further, for each layout, there are two points of weighting factors (WF) and total scores (TS). By using the new weighting factors and total scores of layouts a linear function between the defined points are created, representing the total score with respect to the criteria under consideration. Those figures can be used to analyze the sensitivity of one uncertain criterion at a time. The analysis helps to determine the importance of a criteria and by that possibly improving the accuracy of a score or weight.

4.6.1. *Sensitivity Analysis of the 1st Criteria*

The 1st criteria "Entrance of the harbour" has the weighting factor of 0.183. This was increased by 0.10 to 0.283 and the difference divided proportionally within the other criteria so that the total weight of all the factors would still be 1.00 (100%). With the new weighting factors, the highest scored layout remains the same. However, layout 3D and layout 8D switched places as shown in Table 5. As seen from the early mentioned table, the rise of the first criterion importance results in the increase of the layouts scores. Meaning, that the layouts under consideration are good in terms of the 1st criteria. All the results obtained after the first set of sensitivity analysis can be seen in Table 6.

Table 5: Performance Scores after Sensitivity Analysis of Criteria no. 1

Rank	First results	Results after sensitivity analysis of criteria no. 1
1.	Layout 6D – 7.69p	Layout 6D – 7.92p
2.	Layout 6C – 7.60p	Layout 6C – 7.83p
3.	Layout 3D – 7.55p	Layout 8D – 7.77p
4.	Layout 8D – 7.52p	Layout 3D – 7.67p

Table 6: Sensitivity Analysis of Criteria no. 1

SENSITIVITY ANALYSIS ON A&R SHIPYARD SHARED HARBOUR																								
Nr	Criterion	WF	WF (NEW)	LAYOUTS [Give Points 10/10]																				
				Layout 1 (Ref)	Layout 2	Layout 3				Layout 4		Layout 5		Layout 6				Layout 7			Layout 8			
						A	B	C	D	A	B	A	B	A	B	C	D	A	B	C	A	B	C	D
1	Entrance of the harbour	0.183	0.283	5.38	8.04	6.83	7.67	8.50	8.50	7.50	8.50	7.63	8.13	7.83	8.67	9.50	9.50	7.54	7.54	7.54	7.83	8.67	9.50	9.50
2	Maneuverability inside the harbour basin	0.208	0.182	5.06	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.22	7.22	7.22	6.11
3	Time to release a ship	0.120	0.105	1.50	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00
4	Effect of tides/ currents/ sedimentation	0.175	0.154	5.56	7.78	3.33	7.78	8.89	8.89	7.78	7.78	7.78	7.78	3.33	7.78	8.89	8.89	3.33	7.78	8.89	3.33	7.78	8.89	8.89
5	Impact on the marina and its users	0.190	0.167	8.93	7.93	6.87	6.87	6.87	9.00	8.13	8.13	7.93	7.93	7.07	7.07	7.07	8.80	7.93	7.93	7.93	6.87	6.87	6.87	9.00
6	Complexity of the solution and need of public authorisation	0.125	0.110	10.00	6.67	6.67	5.00	5.00	5.00	5.00	5.00	6.67	6.67	6.67	5.00	5.00	5.00	6.67	5.00	5.00	5.00	3.33	3.33	3.33
TOTAL	**OLD**	**1.00**	**1.00**	**6.13**	**7.36**	**6.31**	**7.03**	**7.38**	**7.55**	**7.09**	**7.27**	**7.29**	**7.38**	**6.53**	**7.25**	**7.60**	**7.69**	**6.49**	**7.06**	**7.26**	**6.28**	**7.00**	**7.35**	**7.52**
	NEW			**6.04**	**7.44**	**6.37**	**7.11**	**7.51**	**7.67**	**7.14**	**7.42**	**7.33**	**7.47**	**6.69**	**7.42**	**7.83**	**7.92**	**6.62**	**7.12**	**7.29**	**6.47**	**7.21**	**7.61**	**7.77**

In Figure 19 can be seen the impact of the first criteria to the rank of the top scored layouts. As seen, the layout 3D loses its position when the weight of the first criteria “Entrance to the harbour” is increased to about 0.21. However, as can be seen, the other top scored layouts positions remain practically unaffected when increasing the weighting factor of criteria no. 1.

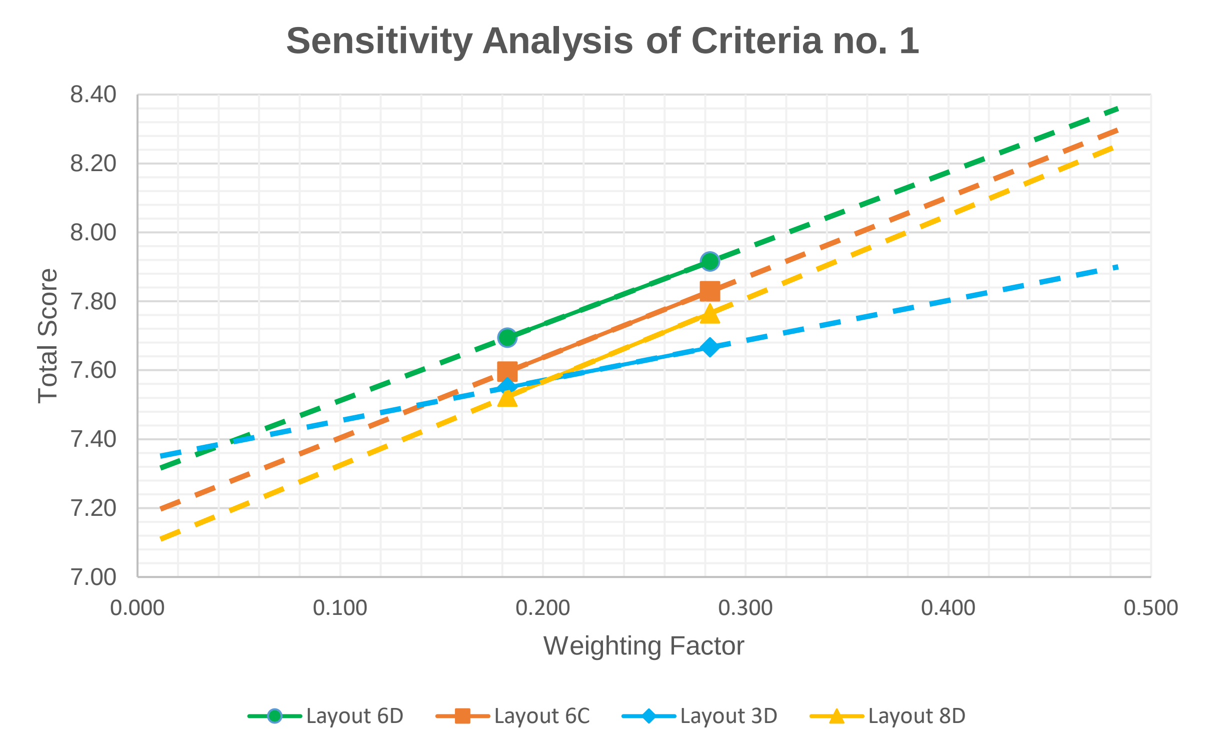

Figure 19: Sensitivity Analysis of Criteria no. 1

4.6.2. Sensitivity Analysis of the 2nd Criteria

The 2nd criteria “Manoeuvrability inside the harbour basin” has the highest weighting factor of 0.208. This was increased by 0.10 to 0.308 and the difference divided proportionally within the other criteria so that the total weight of all the factors would still be 1.00 (100%). With the new weighting factor, the rank of the layouts changed drastically. This means that the second criteria is relatively sensitive and has a great impact on the outcome. The four top scored layout before and after can be seen in Table 7. All the results achieved are presented in Table 8.

Table 7: Performance Scores after Sensitivity Analysis of Criteria no. 2

Rank	First results	Results after sensitivity analysis of criteria no. 2
1.	Layout 6D – 7.69p	Layout 6C – 7.55p
2.	Layout 6C – 7.60p	Layout 6D – 7.49p
3.	Layout 3D – 7.55p	Layout 5B – 7.41p
4.	Layout 8D – 7.52p	Layout 2 – 7.40p

Table 8: Sensitivity Analysis of Criteria no. 2

SENSITIVITY ANALYSIS ON A&R SHIPYARD SHARED HARBOUR

No	Criterion	WF	WF (NEW)	LAYOUTS [Give Points 10/10]																				
				Layout 1 (Ref)	Layout 2	Layout 3				Layout 4		Layout 5		Layout 6				Layout 7			Layout 8			
						A	B	C	D	A	B	A	B	A	B	C	D	A	B	C	A	B	C	D
1	Entrance of the harbour	0.183	0.159	5.38	8.04	6.83	7.67	8.50	8.50	7.50	8.50	7.63	8.13	7.83	8.67	9.50	9.50	7.54	7.54	7.54	7.83	8.67	9.50	9.50
2	Maneuverability inside the harbour basin	0.208	0.308	5.06	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.22	7.22	7.22	6.11
3	Time to release a ship	0.120	0.105	1.50	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00
4	Effect of tides/ currents/ sedimentation	0.175	0.153	5.56	7.78	3.33	7.78	8.89	8.89	7.78	7.78	7.78	7.78	3.33	7.78	8.89	8.89	3.33	7.78	8.89	3.33	7.78	8.89	8.89
5	Impact on the marina and its users	0.190	0.166	8.93	7.93	6.87	6.87	6.87	9.00	8.13	8.13	7.93	7.93	7.07	7.07	7.07	8.80	7.93	7.93	7.93	6.87	6.87	6.87	9.00
6	Complexity of the solution and need of public authorisation	0.125	0.109	10.00	6.67	6.67	5.00	5.00	5.00	5.00	5.00	6.67	6.67	6.67	5.00	5.00	5.00	6.67	5.00	5.00	5.00	3.33	3.33	3.33
TOTAL	**OLD**	**1.00**	**1.00**	**6.13**	**7.36**	**6.31**	**7.03**	**7.38**	**7.55**	**7.09**	**7.27**	**7.29**	**7.38**	**6.53**	**7.25**	**7.60**	**7.69**	**6.49**	**7.06**	**7.26**	**6.28**	**7.00**	**7.35**	**7.52**
	NEW			**5.99**	**7.40**	**6.42**	**7.05**	**7.36**	**7.37**	**7.16**	**7.32**	**7.33**	**7.41**	**6.62**	**7.25**	**7.55**	**7.49**	**6.64**	**7.14**	**7.31**	**6.40**	**7.03**	**7.33**	**7.35**

In Figure 20 can be seen the impact of the second criteria to the rank of the top scored layouts. As seen, the layout 6D loses its position to layout 6C, layout 3D rank drops a lot and its position is taken by layout 5B. Layout 2 rises up and takes the position of layout 8D. This is a clear indicator that the second criteria's weighting factor plays a crucial role in the ranking of the layouts. As can be seen, if the weighting factor would be increased even higher than done, layout 2 and layout 5B would start to score better than others. It is very likely, that if the weight would be increased e.g. by 0.2, other layouts participating in the analysis, but have a lower score, would start to show themselves. Furthermore, the increase of criteria no 2 importance, decreases the scores of the layouts. This means, that the layouts are not so good in terms of maneuverability inside the harbour basin, however, that is justified by the fact that the basins territory is quite narrow and there is not much room to expand.

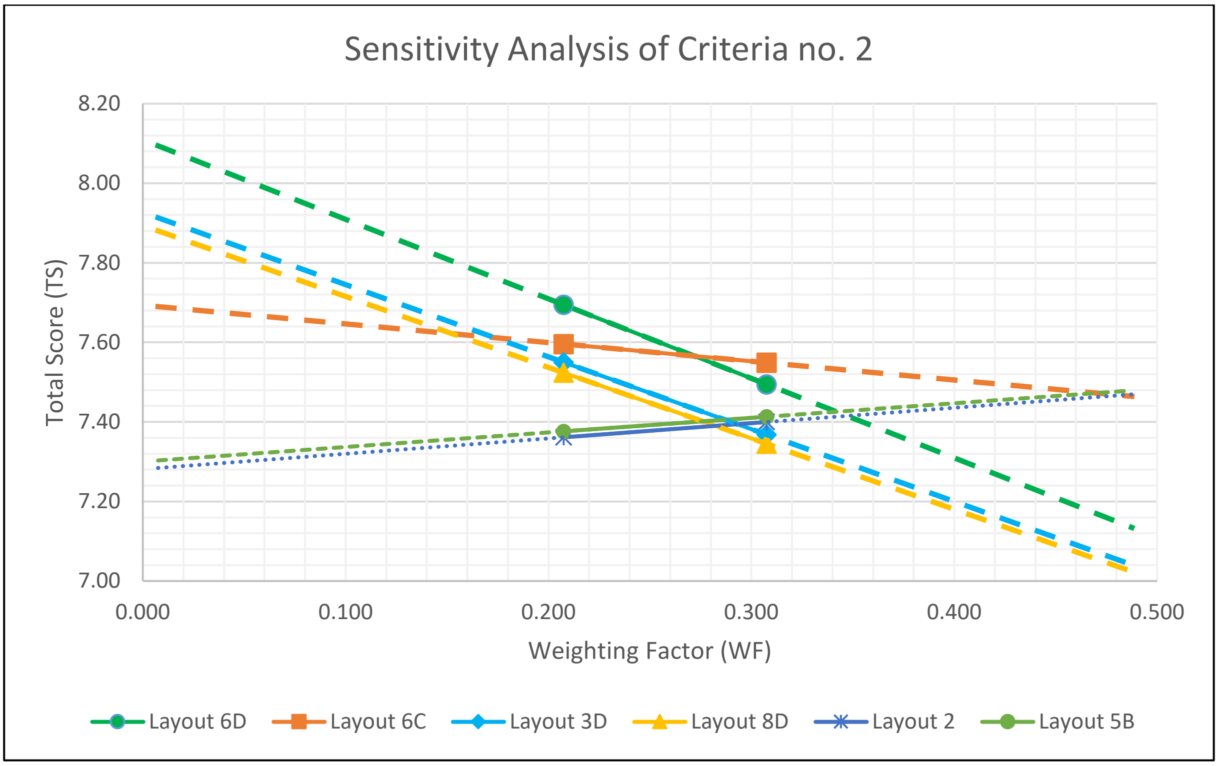

Figure 20: Sensitivity Analysis of Criteria no. 2

4.6.3. Sensitivity Analysis of the 3rd Criteria

The 3rd criteria "Time to release a ship" has initially the lowest weighting factor of 0.120. This was increased by 0.10 to 0.220 and the difference divided proportionally within the other criteria. With the new weighting factor, the rank of the layouts did not change at all. This means, that the criteria has a very minor impact on the rank if any. However, as the rank of the layours reamind the same, their score dropped compared to the initial analysis. The top scored layouts can be seen in Table 9.

Table 9: Sensitivity Analysis of Criteria no. 3

SENSITIVITY ANALYSIS ON A&R SHIPYARD SHARED HARBOUR																								
No	Criterion	WF	WF (NEW)	LAYOUTS [Give Points 10/10]																				
				Layout 1 (Ref)	Layout 2	Layout 3				Layout 4		Layout 5		Layout 6				Layout 7			Layout 8			
						A	B	C	D	A	B	A	B	A	B	C	D	A	B	C	A	B	C	D
1	Entrance of the harbour	0.183	0.162	5.38	8.04	6.83	7.67	8.50	8.50	7.50	8.50	7.63	8.13	7.83	8.67	9.50	9.50	7.54	7.54	7.54	7.83	8.67	9.50	9.50
2	Maneuverability inside the harbour basin	0.208	0.184	5.06	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.22	7.22	7.22	6.11
3	Time to release a ship	0.120	0.220	1.50	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00
4	Effect of tides/ currents/ sedimentation	0.175	0.155	5.56	7.78	3.33	7.78	8.89	8.89	7.78	7.78	7.78	7.78	3.33	7.78	8.89	8.89	3.33	7.78	8.89	3.33	7.78	8.89	8.89
5	Impact on the marina and its users	0.190	0.168	8.93	7.93	6.87	6.87	6.87	9.00	8.13	8.13	7.93	7.93	7.07	7.07	7.07	8.80	7.93	7.93	7.93	6.87	6.87	6.87	9.00
6	Complexity of the solution and need of public authorisation	0.125	0.111	10.00	6.67	6.67	5.00	5.00	5.00	5.00	5.00	6.67	6.67	6.67	5.00	5.00	5.00	6.67	5.00	5.00	5.00	3.33	3.33	3.33
TOTAL	**OLD**	**1.00**	**1.00**	**6.13**	**7.36**	**6.31**	**7.03**	**7.38**	**7.55**	**7.09**	**7.27**	**7.29**	**7.38**	**6.53**	**7.25**	**7.60**	**7.69**	**6.49**	**7.06**	**7.26**	**6.28**	**7.00**	**7.35**	**7.52**
	NEW			**5.60**	**7.09**	**6.39**	**7.03**	**7.33**	**7.49**	**6.85**	**7.02**	**7.03**	**7.11**	**6.58**	**7.22**	**7.53**	**7.62**	**6.32**	**6.83**	**7.00**	**6.36**	**7.00**	**7.31**	**7.46**

Figure 21 presents the sensitivity of the third criteria. As it can be observed, the increase of the weighting factor did not have any impact on the positions of the layouts. However, by increasing the weight, the total score of the layouts decreases. This means that the layouts are not that perfect in terms of the third criteria, as if the criteria's weight becomes higher, the scores of the layouts drop.

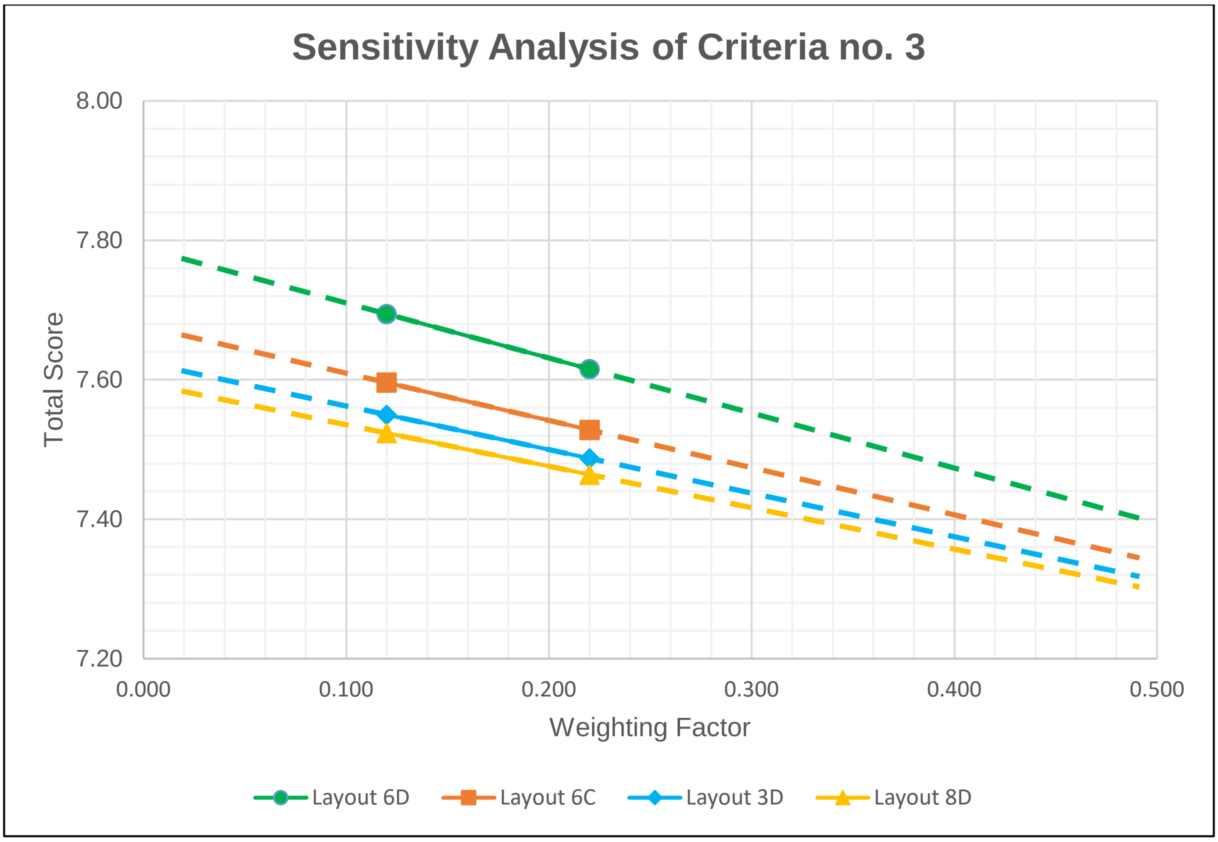

Figure 21: Sensitivity Analysis of Criteria no. 3

4.6.4. Sensitivity Analysis of the 4th Criteria

The 4th criteria "Effect of tides/ currents/ sedimentation" has the weighting factor of 0.175. This was increased by 0.10 to 0.275 and the difference divided proportionally within the other criteria. With the new weighting factor, the rank of the layouts remained unchanged, meaning the impact of the criteria under consideration to the positions of the layouts is negligible. However, the scores of the layouts increased, meaning, that the layouts are good in terms of the 4th criteria. The top scored layouts can be seen in Table 10.

Table 10: Sensitivity Analysis of Criteria no. 4

SENSITIVITY ANALYSIS ON A&R SHIPYARD SHARED HARBOUR																								
No	Criterion	WF	WF (NEW)	LAYOUTS [Give Points 10/10]																				
				Layout 1 (Ref)	Layout 2	Layout 3				Layout 4		Layout 5		Layout 6				Layout 7			Layout 8			
						A	B	C	D	A	B	A	B	A	B	C	D	A	B	C	A	B	C	D
1	Entrance of the harbour	0.183	0.160	5.38	8.04	6.83	7.67	8.50	8.50	7.50	8.50	7.63	8.13	7.83	8.67	9.50	9.50	7.54	7.54	7.54	7.83	8.67	9.50	9.50
2	Maneuverability inside the harbour basin	0.208	0.182	5.06	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.22	7.22	7.22	6.11
3	Time to release a ship	0.120	0.105	1.50	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00
4	Effect of tides/ currents/ sedimentation	0.175	0.275	5.56	7.78	3.33	7.78	8.89	8.89	7.78	7.78	7.78	7.78	3.33	7.78	8.89	8.89	3.33	7.78	8.89	3.33	7.78	8.89	8.89
5	Impact on the marina and its users	0.190	0.167	8.93	7.93	6.87	6.87	6.87	9.00	8.13	8.13	7.93	7.93	7.07	7.07	7.07	8.80	7.93	7.93	7.93	6.87	6.87	6.87	9.00
6	Complexity of the solution and need of public authorisation	0.125	0.110	10.00	6.67	6.67	5.00	5.00	5.00	5.00	5.00	6.67	6.67	6.67	5.00	5.00	5.00	6.67	5.00	5.00	5.00	3.33	3.33	3.33
TOTAL	**OLD**	**1.00**	**1.00**	**6.13**	**7.36**	**6.31**	**7.03**	**7.38**	**7.55**	**7.09**	**7.27**	**7.29**	**7.38**	**6.53**	**7.25**	**7.60**	**7.69**	**6.49**	**7.06**	**7.26**	**6.28**	**7.00**	**7.35**	**7.52**
	NEW			**6.06**	**7.41**	**5.95**	**7.12**	**7.56**	**7.71**	**7.17**	**7.34**	**7.35**	**7.43**	**6.14**	**7.31**	**7.75**	**7.84**	**6.11**	**7.15**	**7.45**	**5.92**	**7.10**	**7.54**	**7.69**

Figure 22 presents the sensitivity analysis of criteria no. 4. As seen, the results remain unaffected by changing the criteria's weight as the positions of the layouts stay the same. However, by increasing the importance of criteria no 4, the scores of the layouts increase, which means that the layouts are good in terms of the 4th criteria.

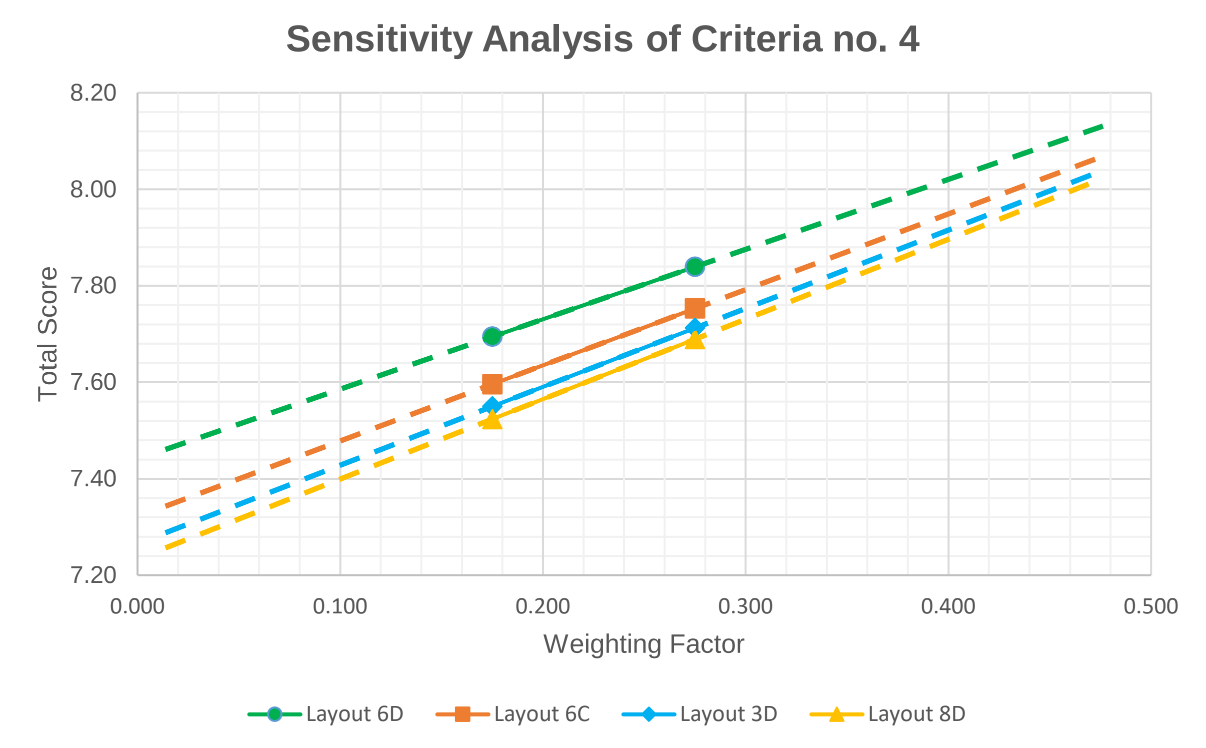

Figure 22: Sensitivity Analysis of Criteria no. 4

4.6.5. Sensitivity Analysis of the 5th Criteria

The 5th criteria "Impact on the marina and its users" has the weighting factor of 0.190. It was decided to increase its weight by 0.20 to 0.390. With the new weighting factor, the ranks of the layouts changed, resulting in the downfall of layout 6C and in a great increase of layout 5B. The initial rank compared to the new rank can be seen in Table 11. All the scores can be seen in Table 12. As seen from the aforementioned tables, some layouts scores increase, meaning that those layouts are good in terms of the 5th criteria.

Table 11: Performance Scores after Sensitivity Analysis of Criteria no. 5

Rank	First results	Results after sensitivity analysis of criteria no. 5
1.	Layout 6D – 7.69p	Layout 6D – 7.97p
2.	Layout 6C – 7.60p	Layout 3D– 7.91p
3.	Layout 3D – 7.55p	Layout 8D – 7.89p
4.	Layout 8D – 7.52p	Layout 5B – 7.51p

Table 12: Sensitivity Analysis of Criteria no. 5

SENSITIVITY ANALYSIS ON A&R SHIPYARD SHARED HARBOUR																								
No	Criterion	WF	WF (NEW)	LAYOUTS [Give Points 10/10]																				
				Layout 1 (Ref)	Layout 2	Layout 3				Layout 4		Layout 5		Layout 6				Layout 7			Layout 8			
						A	B	C	D	A	B	A	B	A	B	C	D	A	B	C	A	B	C	D
1	Entrance of the harbour	0.183	0.137	5.38	8.04	6.83	7.67	8.50	8.50	7.50	8.50	7.63	8.13	7.83	8.67	9.50	9.50	7.54	7.54	7.54	7.83	8.67	9.50	9.50
2	Maneuverability inside the harbour basin	0.208	0.156	5.06	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.22	7.22	7.22	6.11
3	Time to release a ship	0.120	0.090	1.50	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00
4	Effect of tides/ currents/ sedimentation	0.175	0.132	5.56	7.78	3.33	7.78	8.89	8.89	7.78	7.78	7.78	7.78	3.33	7.78	8.89	8.89	3.33	7.78	8.89	3.33	7.78	8.89	8.89
5	Impact on the marina and its users	0.190	0.390	8.93	7.93	6.87	6.87	6.87	9.00	8.13	8.13	7.93	7.93	7.07	7.07	7.07	8.80	7.93	7.93	7.93	6.87	6.87	6.87	9.00
6	Complexity of the solution and need of public authorisation	0.125	0.094	10.00	6.67	6.67	5.00	5.00	5.00	5.00	5.00	6.67	6.67	6.67	5.00	5.00	5.00	6.67	5.00	5.00	5.00	3.33	3.33	3.33
TOTAL	OLD	1.00	1.00	6.13	7.36	6.31	7.03	7.38	7.55	7.09	7.27	7.29	7.38	6.53	7.25	7.60	7.69	6.49	7.06	7.26	6.28	7.00	7.35	7.52
	NEW			6.82	7.50	6.44	6.99	7.25	7.91	7.35	7.49	7.45	7.51	6.66	7.20	7.47	7.97	6.85	7.28	7.42	6.43	6.97	7.23	7.89

Figure 23 presents the sensitivity analysis of criteria no. 5. As it can be seen, the increase in the weighting factor has an impact on the results, as layout 6C is no longer competitive and layout 5B takes its position at the weight factor of about 0.35. The number one scored layout 6D remains competitive until the weight of around 0.53 and then starts to lose its position to layout 3D and layout 8D. Probably this criterion serves as the most important to the local Lemwerder Yacht Club. However, as the weighting factor was increased in order to demonstrate the impact of the criteria under consideration, it decreases the other criteria's weighting factors and by that having actually a negative effect, as the layout 8D position increases. As the layout 8D is more complex in terms of gaining approval it has to be viewed far more critically.

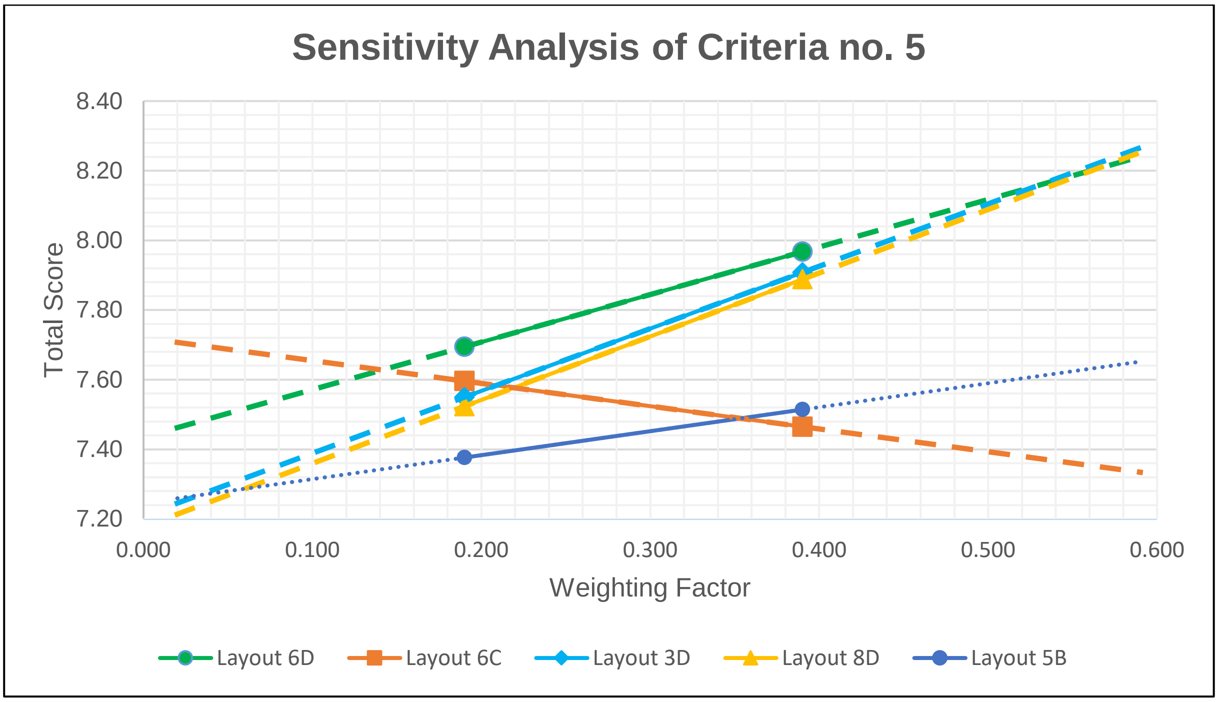

Figure 23: Sensitivity Analysis of Criteria no. 5

4.6.6. Sensitivity Analysis of the 6th Criteria

The 6th criteria "Complexity of the solution and need of public authorisation" serves probably one of the most important criteria's as it is directly linked to the approval, cost and time of construction. Initially, it has the weighting factor of 0.125 and was increased by 0.10 to 0.225. By increasing the criteria's weigh it has a great impact on results as can be seen in Table 13&14.

Table 13: Performance Scores after Sensitivity Analysis of Criteria no. 6

Rank	First results	Results after sensitivity analysis of criteria no. 6
1.	Layout 6D – 7.69p	Layout 6D – 7.39p
2.	Layout 6C – 7.60p	Layout 6C– 7.30p
3.	Layout 3D – 7.55p	Layout 5B – 7.30p
4.	Layout 8D – 7.52p	Layout 2– 7.28p

Table 14: Sensitivity Analysis of Criteria no. 6

SENSITIVITY ANALYSIS ON A&R SHIPYARD SHARED HARBOUR																								
No	Criterion	WF	WF (NEW)	LAYOUTS [Give Points 10/10]																				
				Layout 1 (Ref)	Layout 2	Layout 3				Layout 4		Layout 5		Layout 6				Layout 7			Layout 8			
						A	B	C	D	A	B	A	B	A	B	C	D	A	B	C	A	B	C	D
1	Entrance of the harbour	0.183	0.162	5.38	8.04	6.83	7.67	8.50	8.50	7.50	8.50	7.63	8.13	7.83	8.67	9.50	9.50	7.54	7.54	7.54	7.83	8.67	9.50	9.50
2	Maneuverability inside the harbour basin	0.208	0.184	5.06	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.67	7.22	7.22	7.22	6.11	7.67	7.67	7.67	7.22	7.22	7.22	6.11
3	Time to release a ship	0.120	0.106	1.50	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00
4	Effect of tides/ currents/ sedimentation	0.175	0.155	5.56	7.78	3.33	7.78	8.89	8.89	7.78	7.78	7.78	7.78	3.33	7.78	8.89	8.89	3.33	7.78	8.89	3.33	7.78	8.89	8.89
5	Impact on the marina and its users	0.190	0.168	8.93	7.93	6.87	6.87	6.87	9.00	8.13	8.13	7.93	7.93	7.07	7.07	7.07	8.80	7.93	7.93	7.93	6.87	6.87	6.87	9.00
6	Complexity of the solution and need of public authorisation	0.125	0.225	10.00	6.67	6.67	5.00	5.00	5.00	5.00	5.00	6.67	6.67	6.67	5.00	5.00	5.00	6.67	5.00	5.00	5.00	3.33	3.33	3.33
TOTAL	**OLD**	**1.00**	**1.00**	**6.13**	**7.36**	**6.31**	**7.03**	**7.38**	**7.55**	**7.09**	**7.27**	**7.29**	**7.38**	**6.53**	**7.25**	**7.60**	**7.69**	**6.49**	**7.06**	**7.26**	**6.28**	**7.00**	**7.35**	**7.52**
	NEW			**6.57**	**7.28**	**6.35**	**6.80**	**7.10**	**7.26**	**6.85**	**7.01**	**7.21**	**7.30**	**6.54**	**6.99**	**7.30**	**7.39**	**6.51**	**6.83**	**7.00**	**6.13**	**6.58**	**6.89**	**7.04**

Figure 24 presents the sensitivity analysis of criteria no. 6. As it can be seen, the increase in the weighting factor has a great impact on the ranks, resulting in the downfall of all the top four scored layouts by the multi-criteria analysis and in the rise of the position of layout 5B and layout 2 (Table 13). At the weighting factor of about 0.26 none of the initial top scored layouts remain competitive. As seen, layout 8D has a very huge drop. It is justified by the fact that this layout is more complex and requires higher public authorization as the sheet pile wall extends to the navigation channel. Thus, probably resulting in a higher cost and longer time span in the realization of layout 8D. Furthermore, as can be seen from the results (Table 14), by increasing the importance of the 6th criteria, it practically decreases the scores of all of the layouts. This can be justified by the fact that the sheet pile wall of almost all of the layouts moves closer to the boundaries of the navigation channel. However, as the sheet pile wall of layout 8D crosses the currently set boundary line of the navigation channel, this layout has the highest drop in its score, as it is affected more by the importance of the 6th criteria than other layouts.

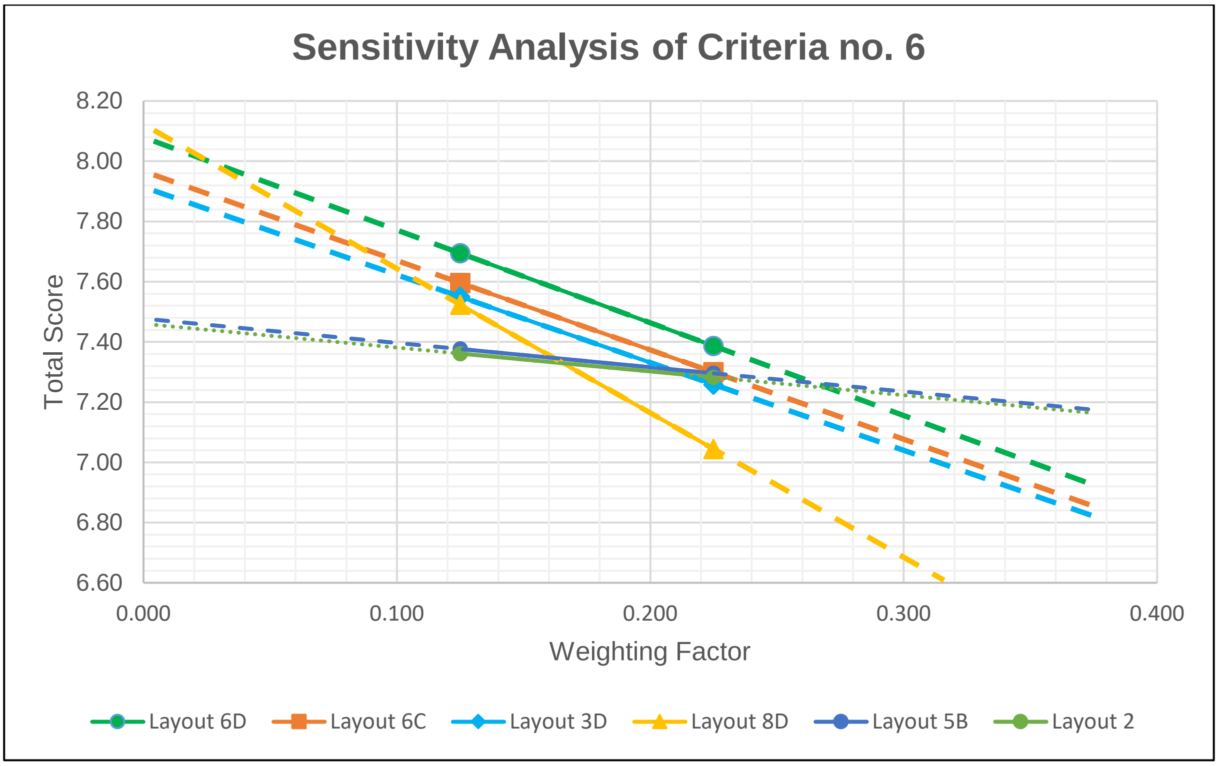

Figure 24: Sensitivity Analysis of Criteria no. 6

4.7. Conclusion of the Sensitivity Analysis

From the above results can be seen, that on the one hand some layouts are rather sensitive to a decrease or increase in the weighting factor of a criteria and therefore change the scores drastically, on the other hand, some criteria's weight does not affect much the scores.

By looking at the results obtained, the change in the 2nd, the 5th and the 6th criteria's weight causes the highest diversity in the scores. However, the most important of them can be considered the 6th criteria "Complexity of the solution and need of public authorisation". It is because this criterion separates the more challenging solutions from the less complicated solutions. Furthermore, this criterion can be considered directly linked to final cost and to the realization time of a layout. Therefore, in order to separate the less and more complicated solutions, it could be worth to consider changing the 6th criteria's weight higher.

Furthermore, by increasing the importance of one criteria at a time, it shows also how good is the design and arrangement of a layout with respect to the criteria under consideration. If a layouts new score rises after the increase of a criterions importance, it means that the layout is better in terms of the considered criteria.

In addition to, in the report of Design of Movable Weirs and Storm Surge Barriers by PIANC-WG26 (2005) [10] it is advised, that it is not recommended to focus entirely on the so-called sensitivity analysis and to use it as a last resort for assessments. However, it is a perfect tool for determining a criteria's importance and can be used to help in improving the accuracy of a weight or score.

To sum up, as the assessors who participated in the analysis gave their opinion and weights for each factor, it is decided to proceed with the top four scored layouts of the multi-criteria analysis (MCA). Here the so-called sensitivity analysis serves as an extra to express a criteria's importance and its influence on the scores of the layouts and the fact, that if sometime in the future it is actually decided to reconstruct the harbour and it is necessary to deliberate over a criteria's importance then the effects can be estimated. All the 21 layouts that were included in the analysis can be seen in APPENDIX II. The final four layouts in a more detail manner are presented in APPENDIX III.

5. DESIGN PROPOSAL FOR THE HARBOUR INTERIOR

5.1. General

The main goal is to achieve in a harbour layout(s) that satisfies the two stakeholders. In order to do that a multi-criteria analysis was performed to select out the best brainstormed layout solutions. As a result of the analysis, the four top scored layouts are: layout 6D, 6C, 3D and 8D which can be also viewed in detail in APPENDIX III.

The main key point of all the aforementioned layouts is their design. Fundamentally they differ in the design arrangement of the floating marina, in number of boat places, the size and shape of the sheet-pile wall and in the location and width of the harbour entrance. Of course, there could have been more modifications and the layouts more unlike, but then again they would have been harder to compare. Not to mention, all the layouts have been generated the way that they represent the needs of the stakeholders. The needs of the stakeholders were identified by having multiple sessions of interviews with them.

5.2. Layout design

5.2.1. Protecting wall

It was decided that the harbour protecting wall would be made of steel sheet-piles that are rammed to the river bed to a certain height. The sheet-piles should be rammed in parallel rows, connected with tie rods and filled with earth, by forming a steel sheet-pile cofferdam. This type of wall is more efficient in narrow places and in places, where there is quite deep. A rubble mound wall would be out of the question in such a location. Furthermore, the protecting wall also serves as a docking place and watertight construction, by which to ensure the constant water level in the harbour basin.

Furthermore, the entrance perimeter has to be made from steel or reinforced concrete. The foundation of the entrance gate should be made from piles dredged into the riverbed, by that forming a watertight seal. On top of which should be resting the reinforced concrete foundation. That way the leakage from the harbour to the river will be kept minimum. Under this framework, the foundation of the entrance gate and its perimeter are not analysed further.

As the construction type of the wall is same for all the layouts, its preliminary design and calculations can be observed under chapter 6.

5.2.2. *Entrance gate*

As can be seen from the top scored layouts, all of them have two access gates to the harbour. This benefits both of the stakeholders, as the bigger gate could remain closed most of the time. The bigger gate would mainly be used by the shipyard if a vessel is launched or docked inside the harbour. The smaller gate would be used by the marina users to access the harbour with pleasure crafts. The two gate system proves to be the best, as the width of the smaller entrance, that ought to be used during navigation season, is decreased and therefore results in less sedimentation coming in. Moreover, both of the gates are intended to be closed during winter seasons and only opened for specific use only during that time. As can be observed from the results achieved in paragraph 3.2, that way it is possible to avoid more than 50% of sedimentation.

Both of the entrance gates chosen are to be of floating door type gates, as they are relatively easy to maintain and low in initial cost compared to more mechanical gates e.g. sliding gates. Furthermore, the bigger entrance gate is for the use of A&R shipyard and probably needs the help of tugboats to be moved or manoeuvred. However, the smaller entrance gate, which is designed for the marina users, can be moved and manoeuvred by the use of ropes. The preliminary design and calculations are done only for the larger gate, which can be seen in chapter 7. Anyhow, both of the gates need considerable manpower to handle them. In addition, an alternative solution for the entrance gate is also proposed under chapter 7.6.

5.2.3. *Marina in the shared harbour*

The marina inside the shared harbour is designed using the recommendations given in The Yacht Harbour Association LTD (2013) [2] and regarding the experience of Top Marine OÜ (2016) [12]. One of the major criteria designing the marina was the number of boat places. The absolute minimum requirement was that it would remain the same. However, the goal still was to have more boat places of bigger size and room for growth. The current number of boat places, as well as the size range of the boats, can be seen in Table 15.

Table 15: Current Number of Boat Places

Boat Length Range (m)		Number of Those Boats
0.00	6.10	31
6.11	7.60	19
7.61	9.10	28
9.11	10.70	15
10.71	12.20	5
12.21	13.70	2
13.71	15.20	1
TOTAL		**101**

** Data received by personal communication with a member of the local Yacht Club.*

Based on the data received from the Yacht Club and regarding the technical data sheets gained from Top Marine OÜ (2016) [12], Table 16 was generated to express the top scored layouts berth width, length of mooring fingers and the total number of boats.

Table 16: Marina Data of the Top Scored Layouts

Berth Width (m)	Length of Mooring Finger (m)	Length of Boat Boom (m)	Boat Length Range (m)		No of Boat Places			
					Layout 3D	Layout 6C	Layout 6D	Layout 8D
5.70	-	5.00	0.00	6.10		32		
6.91	6.00	-	6.11	7.60		18		
7.81	7.00	-	7.61	9.10	80	36	80	80
8.71	8.00	-	9.11	10.70				
9.61	9.00	-	10.71	12.20	26	16	20	26
10.51	10.50	-	12.21	13.70				
11.41	12.00	-	13.71	15.20	4	3	5	4
				TOTAL	**110**	**105**	**105**	**110**

** Berth widths and lengths of fingers are taken from the datasheets of a marina design and supplier company in the Nordic countries Top Marine OÜ (2016) [12]*

As it can be seen from the above Table 16, the number of boat places on the top scored layouts is more than on the current layout, however not drastically.

By comparing Table 15 and Table 16 can be seen, the new layouts have some room for growth as there are more places for bigger boats.

The new layouts floating marina elements such as pontoons, gangways and mooring fingers are taken from the materials available from Top Marine OÜ (2016) [12]. Whenever a launching operation by barge is done by A&R, the floating marina needs to be dismantled. This means, that the pontoons need to be quite low in weight and their mooring system relatively easy to handle. That is why the author of this thesis decided to use the product “Boat Pontoon with Plastic Floats” together with the product “Boat boom” and “Mooring Finger” from the product selection of Top Marine OÜ (2016) [12]. The solution proposed can be seen in Figure 25.

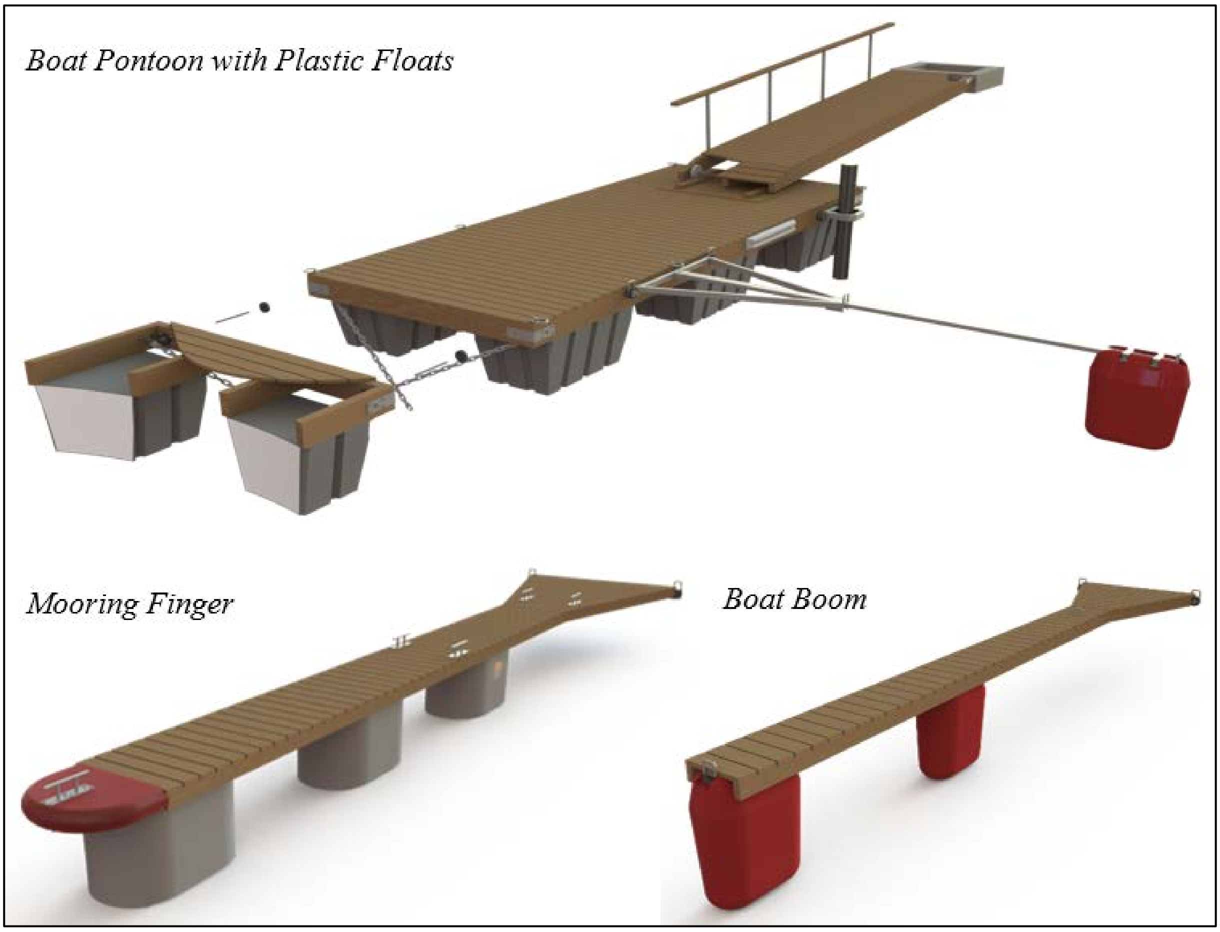

Figure 25: Boat Pontoon with Plastic Floats together with Mooring Finger and Boat Boom [12] (http://www.topmarine.ee/)

Figure 25 presents how the mooring fingers would be connected to the boat pontoon. The pontoon itself, however, needs to be anchored by the use of piles in order to ensure vertical movement together with the tides. As an alternative, some other mooring systems could be explored. For example Seaflex mooring system – an elastic mooring solution for pontoons, that uses bottom anchors and an elastic rope (http://www.seaflex.net/).

6. SHEET PILE COFFERDAM

6.1. General

In the observable harbour, only steel elements such as sheet piles and tie rods were used for the design of the cofferdam. The sheet piles are located partially penetrated in the river bed, in water and under atmospheric condition. The corrosion factor would be the highest in the part that is directly in contact with the tides, meaning dry and wet by turns. The tie rods are located between the parallel rows of sheet piles by connecting them. The gap between the sheet pile walls is meant to be filled with sand.

The water level fluctuation in the lower Weser region can reach 5m or even more. By the personal communication with the stakeholders and considering their long-term experience and taking into account the data provided in Deutsches Gewässerkundliches Jahrbuch (1980-2014) [8] the sheet-pile cofferdam design and calculations are done for the water level difference of 5m. Meaning, on the harbour side it is considered with high water level (HWL) +3.00m NN (NN = Normal-Null or Normal Zero) and in the river side with low water level (SKN=LAT) -2.00m NN. This factor was chosen because A&R would like to maintain high water level in the harbour during winter seasons by closing it and making the harbour basin independent from the tidal influences. Furthermore, as the existing finger piers height is +5.00m NN there was no point in designing the new sheet-pile cofferdam higher than the existing one.

During extreme cases it is possible, that the water level in the river will rise higher than the +3.00m NN (HWL) value used or drop around -1.0m lower than the SKN (LAT) -2.00m NN value. Therefore, in a real construction project also the extreme cases have to be checked. The most severe condition would be, if the water level difference is higher than the 5m used, resulting in greater hydrostatic pressure. Last but not least, under this framework the water level difference considered is 5m, having the lowest -2.00m NN (SKN) and the highest +3.00 NN (HWL).

The proper design of a sheet-pile structure requires estimation of lateral earth pressure, lateral water pressure, shear strength parameters of the soil, unit weight of the soil and drainage condition in the backfill [13]. The sheet-piles must be penetrated to a specific distance in earth to be stable against applied lateral loads, this depth is called depth of penetration X. The steel sheet-pile wall of the cofferdam is calculated as an anchored sheet pile. This is because the height of the backfill exceeds 6m and the deflections on the sheet pile wall become so great and thereby the depth of penetration as well as the section of the sheet pile will be large. In order to reduce this deflection, the sheet pile is supported from its upper edge (usually the distance from the top 1 to 2m) with the use of an anchor (anchored sheet pile)[13]. There exist two ways to analyse an anchored sheet pile wall:

- Free Earth Support Method;
- Fixed Earth Support Method.

Here it is only used the free earth support method, where the soil is assumed as simply supported. In that method, it is assumed that there is a pin support at the end of the sheet pile and the upper edge of the wall is supported by the anchor. Meaning, the deflection of the sheet pile wall will be similar to the deflections of a simply supported beam as presented in Figure 26.

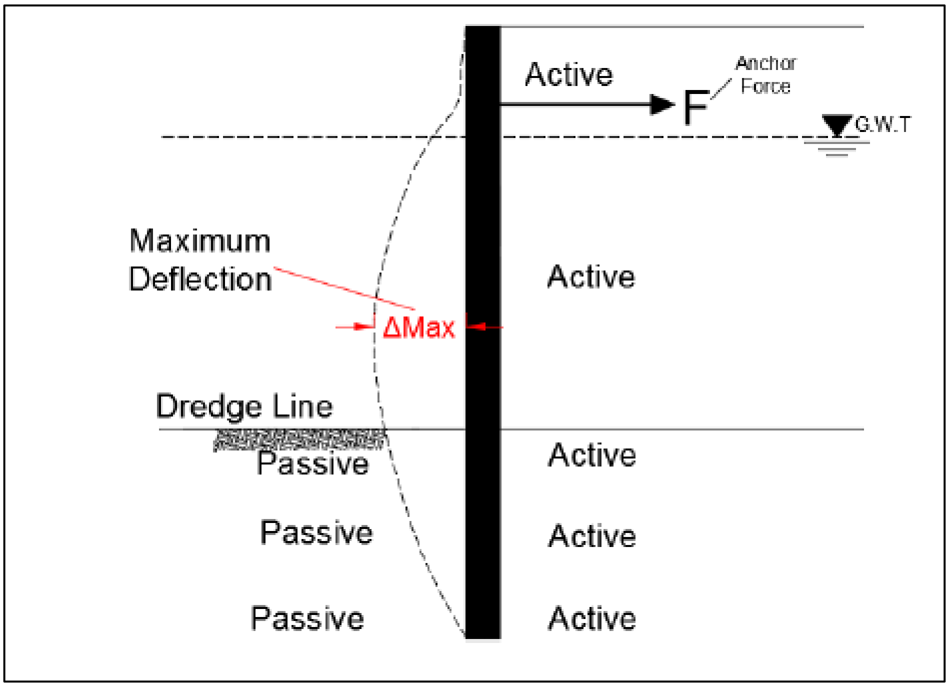

Figure 26: Deflection of the Sheet Pile Wall [13] (http://site.iugaza.edu.ps/iabuzuhri/files/2015/09/Basics-of-Foundation-Engineering-with-Solved-Problems.pdf)

The width of the cofferdam was designed according to the formula presented in https://de.slideshare.net/GaurangK/coffer-dam. It is stated there, that the width of the cofferdam in places where the height (H) of water above the river bed is more than 3m, is calculated following:

$$H > 3 \Rightarrow W = 3 + \frac{1}{2} \cdot (H - 3) = 3 + \frac{1}{2} \cdot (12 - 3) = 7.5\ m \qquad (6.1)$$

Where,

$H - height\ of\ water\ above\ river\ bed\ (m)$

$W - width\ of\ the\ cofferdam\ (m)$

The height of water above river bed is taken $H = 7 + 5 = 12m$, where 7m represents the distance from the river bed -9.00 m NN to the SKN -2.00 m NN and 5m represents the tidal range, resulting total in 12m of water depth. According to formula (6.1) the width of the cofferdam is 7.5m.

6.2. Assumptions

In order to perform a valid analysis, one has to assume the loads acting on the structure. For the sheet pile cofferdam following assumptions are made and validated with the stakeholders:

1) There is no loading from the waves as the site is 60 km inland from the North Sea coast. Therefore the waves generated on the river due to wind or storm are insignificant compared to the hydrostatic loading.
2) There is hydrostatic pressure resulted from the water level differences.
3) Earth pressure (active and passive) acting on the structure.
4) There can be variable horizontal and vertical loading from a vessel docked to the wall, but it is not taken into account here, as it is difficult to assume forces on the pollards in such places where the tidal influence is so huge. Furthermore, from the practice of A&R shipyard could be seen, that a floating concrete pontoon equipped with suitable pollards was connected to the sheet pile wall to ensure the vertical movement with the tides.
5) There is assumed vertical live loading from a mobile crane. Carl A. Thoresen (2003) [14] recommends in the Port Designers Handbook to use as the minimum value $Q_H = 40\ kN/m$.

For the calculations it was assumed that inside the cofferdam the water level is the same as on the harbour side, meaning high water level (HWL). It is because according to the author analysis this case was the worst, resulting in higher active pressure (from the harbour side) and therefore creating a need for a longer and stronger sheet-pile structure. On the following Figure 27 can be seen the considered sheet-pile cofferdams cross-sectional view. The corresponding depths were taken from the Wasser- und Schifffahrtsdirektion Nordwest (2012) [15] layout and validated with the stakeholders.

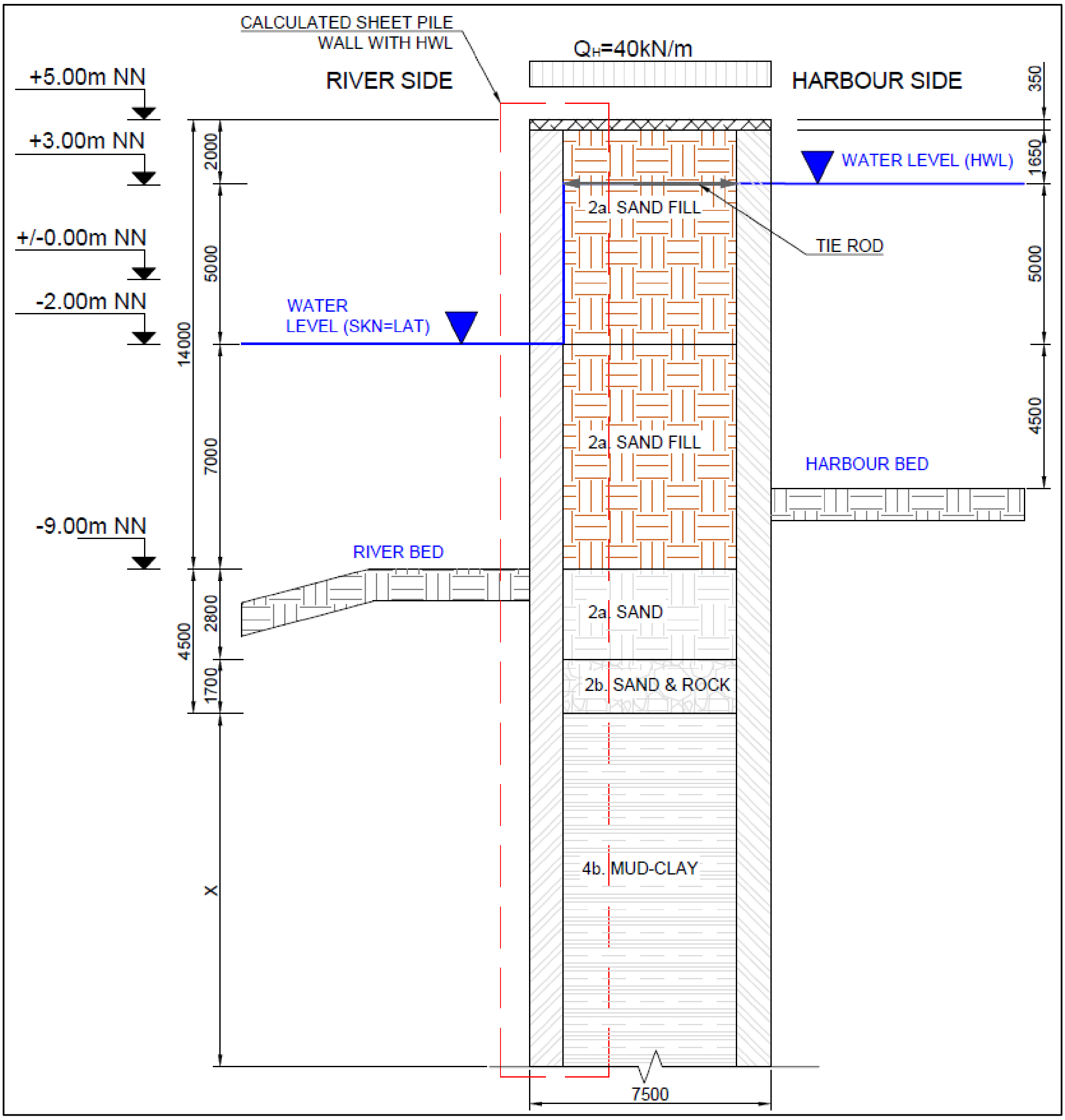

Figure 27: Cross-Sectional View of the Sheet-Pile Cofferdam

From the presented Figure 27 can be seen the analysed sheet pile wall (river side) is surrounded by a red box. The river side was chosen for the calculations, as the depth there is higher and also the loading for that side of the wall is more severe. In addition to, the structure has an anchor on +3.00 NN (2m from the top), connecting the two parallel rows of sheet piles. The structure will be viewed as an anchored sheet-pile wall. For the calculations, an excel spreadsheet was developed.

6.3. Design Approach of the Sheet Pile Wall

According to Eurocode 7-1 (EC 7-1), there are three different design approaches. They mainly differ in the way how the partial factors are distributed among actions, ground properties and resistance. Usually, the design choices are determined nationally and should be stated in the National Annex of EC 7-1. Furthermore, it could be that different problems may be dealt with by different design approaches. In Germany as well in Estonia usually the design approach 2 is used, but it may differ when it does not result in the most economical design, however, the concept of global safety has to be still followed [16]. Different design approaches can be used according to a Eurocode based and widely used Handbook of Construction Engineers used in Estonia, written by Rohusaar, Mägi et al. (2010) [17] if it results in a more economical solution. According to the author calculations for the sheet pile cofferdam, design approach 1.2 gave a more economical solution than the other design approaches mentioned in Eurocode. The partial factors used in design approach 1.2 are following:

3) Partial factor for geotechnical parameters: $\gamma_M = 1.25$
4) Partial factor for variable loads: $\gamma_Q = 1.30$
5) Partial factor for permanent loads: $\gamma_G = 1.00$

6.4. Soil Data and Parameters

In order to perform any sort of analysis and calculations of the sheet-pile wall, one has to know the soil parameters of the site. The soil data was obtained from the geotechnical report of Gruppe Ingenieurbau (2014) [18], made for A&R shipyard. Taken into account the previously stated and considering the new structure that is to be designed, following Table 17 is obtained.

Table 17: Soil Data for the New Construction

No of Layer	Name of the layer	Layer (m) Thickness	c'_k (kPa)	c'_d (kPa)	φ'_k (°)	φ'_d (°)	γ'_k (kN/m^3)	γ'_d (kN/m^3)
1(2a)	Sand (fill)	14.0	0.00	0.00	30.00	24.73	18.00	8.00
2(2a)	Sand	2.8	0.00	0.00	30.00	24.73	18.00	10.00
3(2b)	Sand and Rock	1.7	0.00	0.00	33.00	27.35	18.00	10.00
4(4b)	Mud-Clay	14.3	30.00	24.00	22.50	18.32	20.50	10.50

The shear parameters φ'_k, c'_k, c_u and densities γ'_k, γ'_d of the soil were given in the aforementioned report. Parameters φ'_d, c'_d were calculated based on the initial values by the use of the following formulas:

$$\varphi'_d = arctan\frac{tan\varphi'_k}{\gamma_M} \tag{6.2}$$

And

$$c'_d = \frac{c'_k}{\gamma_M} \tag{6.3}$$

Where,

$\varphi'_d - calculated\ friction\ angle$ (°)

$\varphi'_k - normative\ friction\ angle$ (°)

$c'_d - calculated\ ground\ cohesion\ (kPa)$

$c'_k - normative\ ground\ cohesion\ (kPa)$

$\gamma_M - partial\ factor\ for\ geotechnial\ parameters$

$\gamma'_k - dry\ unit\ weight\ (kN/m^3)$

$\gamma'_d - submerged\ unit\ weight\ (kN/m^3)$

6.5. Calculations

Considered design variable load on the cofferdam:

$$Q_{H,d} = Q_H \cdot \gamma_Q = 40 \cdot 1.30 = 52\ \ kN/m \tag{6.4}$$

Where,

$Q_H - variable\ load\ on\ the\ cofferdam\ (kN/m)$

$\gamma_Q - partial\ factor\ for\ varibale\ loads$

Lateral water pressure:

$$p_H = \rho_f \cdot g \cdot h_d \cdot \gamma_G = 1.0 \cdot 9.81 \cdot 5 \cdot 1.0 \approx 50\ kN/m^2 \tag{6.5}$$

Where,

$\rho_f - water\ density\ of\ fresh\ water\ (t/m^3)$

$g - acceleration\ of\ gravity\ (m/s^2)$

$h_d - differene\ between\ water\ levels\ (m)$

$\gamma_G - partial\ factor\ for\ permanent\ loads$

Weight of the surface (concrete, sand, gravel) considered on the cofferdam:

$$Q_k = \rho \cdot h \cdot \gamma_G = 25 \cdot 0.35 \cdot 1.0 = 8.75\ kN/m^2 \quad (6.6)$$

Where,

$\rho - unit\ weight\ of\ concrete\ (kN/m^3)$

$h - thickness\ of\ the\ surface\ layer\ (m)$

The variable load, as well as the surface load, are being considered basically as an "extra" layer of soil that cause vertical pressure on the structure. The active and passive pressures on the wall are calculated by the use of formulas (6.7) and (6.9).

Active Pressure:

$$\sigma_{a,h} = \sigma_{a,v} \cdot K_a - 2 \cdot c \cdot \sqrt{K_a} \quad (6.7)$$

$$K_a = \tan^2\left(45° - \frac{\varphi'_d}{2}\right) \quad (6.8)$$

Passive pressure:

$$\sigma_{p,h} = \sigma_{p,v} \cdot K_a - 2 \cdot c \cdot \sqrt{K_p} \quad (6.9)$$

$$K_p = \tan^2\left(45° + \frac{\varphi'_d}{2}\right) \quad (6.10)$$

Where,

$\sigma_{a,h} - active\ earth\ pressure\ (kPa)$

$\sigma_{p,h} - passive\ earth\ pressure\ (kPa)$

$\sigma_{a,v} - active\ vertical\ pressure\ from\ the\ soil\ layers\ (kPa)$

$\sigma_{p,v} - passive\ vertical\ pressure\ from\ the\ soil\ layers\ (kPa)$

$c'_d - calculated\ cohesion\ of\ one\ soil\ layer\ (as\ defined\ in$ Table 17) (kPa)

$\varphi'_d - calculated\ friction\ angle\ of\ one\ soil\ layer\ (as\ defined\ in$ Table 17) $(°)$

$K_a - \ transformation\ factor\ of\ active\ vertical\ pressure\ to\ horizontal\ pressure$

$K_p - \ transformation\ factor\ of\ passive\ vertical\ pressure\ to\ horizontal\ pressure$

The only difference in the active and passive earth pressures is in the formula of calculating K. The vertical pressure is calculated by multiplying the thickness of one soil layer with the density of the layer and then adding the previously calculated vertical pressure from the previous layers. By using the aforementioned formulas and the soil data provided in section 6.4 the active and passive pressure were calculated as presented in Table 18 and Table 19.

Table 18: Soil Active Pressure on the Wall

No of Layer	Name of the layer	Soil condition	Depth (m)	Layer Thickness (m)	Ka	Water Pressure (kPa)	σa,v (kPa)	σa,h (kPa)
0	*Load*	Dry	0.00	0.00			60.75	0.00
1(2a)	Sand (fill)		0.00	2.00	0.41	0.00	96.75	24.91
			2.00					39.67
2(2a)	Sand (fill)	Wet	2.00	5.00	0.41	50.00	136.75	39.67
			7.00					106.07
3(2a)	Sand (fill)	Wet	7.00	7.00	0.41	50.00	192.75	106.07
			14.00					129.03
4(2a)	Sand		14.00	2.80	0.41	50.00	220.75	129.03
			16.80					140.51
5(2b)	Sand and Rock		16.80	1.70	0.37	50.00	237.75	131.68
			18.50					137.97
6(4b)	Mud-Clay		18.50	x+18.5	0.52	50.00	237.75+ (x*10.5)*1	139.02
			x					(237.75+(x*10.5)* 1*0.52-34.56)+50

Table 19: Soil Passive Pressure on the Wall

No of Layer	Name of the layer	Soil condition	Depth (m)	Layer Thickness (m)	Kp	Water Pressure (kPa)	σp,v (kPa)	σp,h (kPa)
4(2a)	Sand	Wet	14.00	2.80	2.44	-	28.00	0.00
			16.80					68.32
5(2b)	Sand and Rock		16.80	1.70	2.70	-	45.00	75.60
			18.50					121.50
6(4b)	Mud-Clay		18.50	x+18.5	1.92	-	45+((x)*10.5)*1	152.91
			x					(45+(x*10.5)*1)*1.92-66.72

By combining the results of active and passive pressures Figure 28 is obtained. As can be seen from the figure, the pressure diagram is divided into the shape of rectangles and triangles, where the resultant force acts in the middle of the surface. The penetration depth X of the sheet pile wall can be found from the momentum equilibrium with respect to the anchor (tie rod).

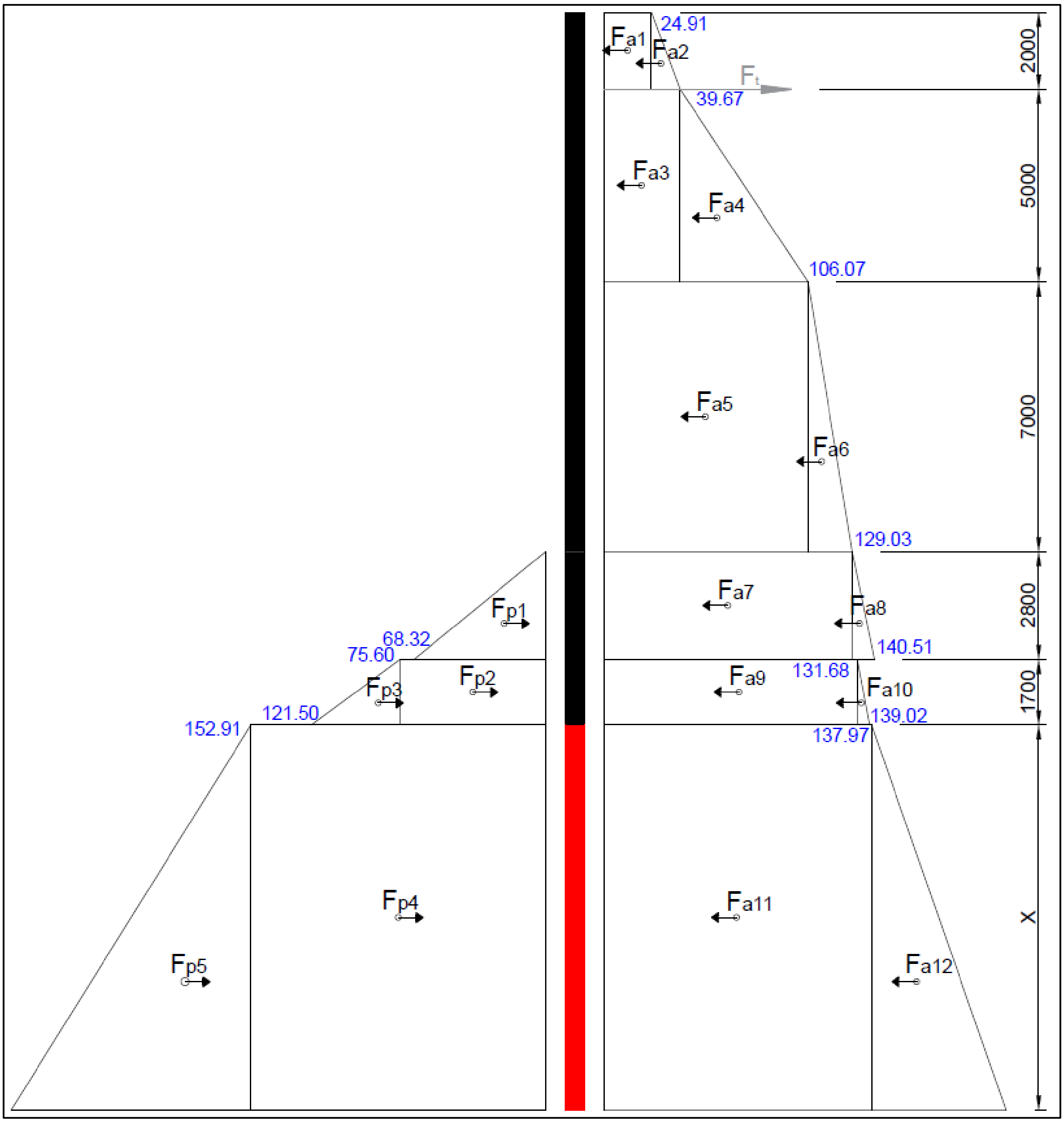

Figure 28: Diagram of Pressures and Resultant Forces

After having found the active and passive pressures on the wall with the use of formulas (6.7)-(6.10) resultant forces as well as moments could be calculated. The forces and moment found can be seen in Table 20 and Table 21.

Table 20: Forces and Moments Induced by Active Pressure

No of Layer	Name of the layer	Depth (m)	Layer Thickness (m)	σa,h (kPa)	Fa (kN/m)	Arm Length (m)	Ma (kNm/m)
1(2a)	Sand (fill)	0.00	2.00	24.91	49.815	-1.00	-49.815
		2.00		39.67	14.76	-0.67	-9.84
2(2a)	Sand (fill)	2.00	5.00	39.67	**198.34**	2.50	495.84
		7.00		106.07	**166.00**	3.33	553.33
3(2a)	Sand (fill)	7.00	7.00	106.07	742.47	8.50	6311.02
		14.00		129.03	80.36	9.67	776.81
4(2a)	Sand	14.00	2.80	129.03	361.28	13.40	4841.11
		16.80		140.51	16.07	13.87	222.87
5(2b)	Sand and Rock	16.80	1.70	131.68	223.85	15.65	3503.28
		18.50		137.97	5.35	15.93	85.19
6(4b)	Mud-Clay	18.50	x	139.02	(x)*139.02	(x/2)+16.5	(x)*139.02* (x/2)+16.5
		x+18.5		5.46*x +139.07	x*(5.46*x +139.07 -139.02)*0.5	(x*2/3) +16.5	x*(5.46*x+139.07 -139.02)*0.5 *(x*2/3)+16.5

Table 21: Forces and Moment Induced by Passive Pressure

No of Layer	Name of the layer	Depth (m)	Layer Thickness (m)	σp,h (kPa)	Fp (kN/m)	Arm Length (m)	Mp (kNm/m)
4(2a)	Sand	14.00	2.80	0.00	0.00	0.00	0.00
		16.80		68.32	95.65	13.87	1326.32
5(2b)	Sand and Rock	16.80	1.70	75.60	128.52	15.65	2011.34
		18.50		121.50	39.02	15.93	621.64
6(4b)	Mud-Clay	18.50	x	152.91	(x)*152.91	(x/2) +16.5	(x)*152.91* (x/2)+16.5
		x+18.5		(45+(x* 10.5)*1)*1.92- 66.72	x*((45+(x* 10.5)*1)* 1.92-66.72- 152.91)*0.5	(x*2/3) +16.5	x*((45+(x* 10.5)*1)* 1.92-66.72 -152.91)*0.5* (x*2/3)+16.5

Where,

$F_a - forces\ induced\ by\ active\ pressure\ (kN/m)$

$F_p - forces\ induced\ by\ passive\ pressure\ (kN/m)$

$M_a - moments\ induced\ by\ active\ pressure\ (kNm/m)$

$M_p - moment\ induced\ by\ passive\ pressure\ (kNm/m)$

The resultant forces F_a and F_p are found by calculating the areas of the rectangular and triangular shaped forms from the pressure diagram (Figure 28). An example has been made. The values calculated as an example can be seen in Table 20 marked as bold.

Forces induced by rectangularly shaped pressure diagram:

$$F_a(F_r) = l_t \cdot \sigma_{a,h(beg)} = 39.67 \cdot 5.00 = 198.35\ kN/m \quad (6.11)$$

Forces induced from triangularly shaped pressure diagram:

$$\begin{aligned} F_a(F_t) &= l_t \cdot \left(\sigma_{a,h\ (end)} - \sigma_{a,h\ (beg)}\right) \cdot 0.5 \\ &= 5.00 \cdot (106.07 - 39.67) \cdot 0.5 = 166.00\ kN/m \end{aligned} \quad (6.12)$$

Where,

$(F_r) - resultant\ forces\ from\ rectangular\ shaped\ pressure\ diagram$

$(F_t) - resultant\ forces\ from\ triangular\ shaped\ pressure\ diagram$

$l_t - layer\ thickness\ of\ soil\ (m)$

$\sigma_{a,h\ (beg)} - pressure\ at\ the\ beginning\ of\ the\ rectangular\ shaped\ pressure\ diagram$

$\sigma_{a,h\ (end)} - pressure\ at\ the\ end\ of\ the\ trinagular\ shaped\ pressure\ diagram$

After finding the resultant forces in the middle of the respective surfaces the arm lengths of those forces will be defined. As presented in Table 20 and Table 21 the arm length of a resultant force is taken with respect to the anchor. The moments from the active and passive pressure are found by multiplying the resultant force with its arms length. The moments calculated are presented in the aforesaid tables.

By summing up the moments in Table 20 and Table 21, we will receive cubic equations for the active and passive side of the wall with respect to the anchor.

For the active side:

$$\sum M_a = 1.82 \cdot x^3 + 114.57 \cdot x^2 + 2294.24 \cdot x + 16729.80 \tag{6.13}$$

For the passive side:

$$\sum M_p = 6.72 \cdot x^3 + 198.37 \cdot x^2 + 1423.87 \cdot x + 3959.30 \tag{6.14}$$

By applying the equilibrium equation:

$$\sum M_a = \sum M_p \tag{6.15}$$

The received cubic equation to be solved is:

$$\sum M = 4.90 \cdot x^3 + 83.79 \cdot x^2 - 870.38 \cdot x - 12770.50 = 0 \tag{6.16}$$

After solving the obtained cubic equation with the help of a webpage "Wolfram Alpha" (available from http://www.wolframalpha.com) the acquired result is $\boldsymbol{X = 12.775\ m}$. This means, that the sheet pile wall has to be penetrated to the mud-clay soil layer by $\mathbf{12.775\ m}$. The total length of the sheet pile wall is: $\boldsymbol{L = 18.5 + 12.775 \approx 31.3\ m}$.

As the sheet pile wall has to be penetrated in total 17.3m into the ground and 12.775m of the wall should be in the mud-clay layer, where the permeability is very small, we can assume that the water level loss in the harbour side due to seepage is very low and therefore is not studied further here. [17]

The total length of the sheet pile wall with pressure diagram can be seen in Figure 29.

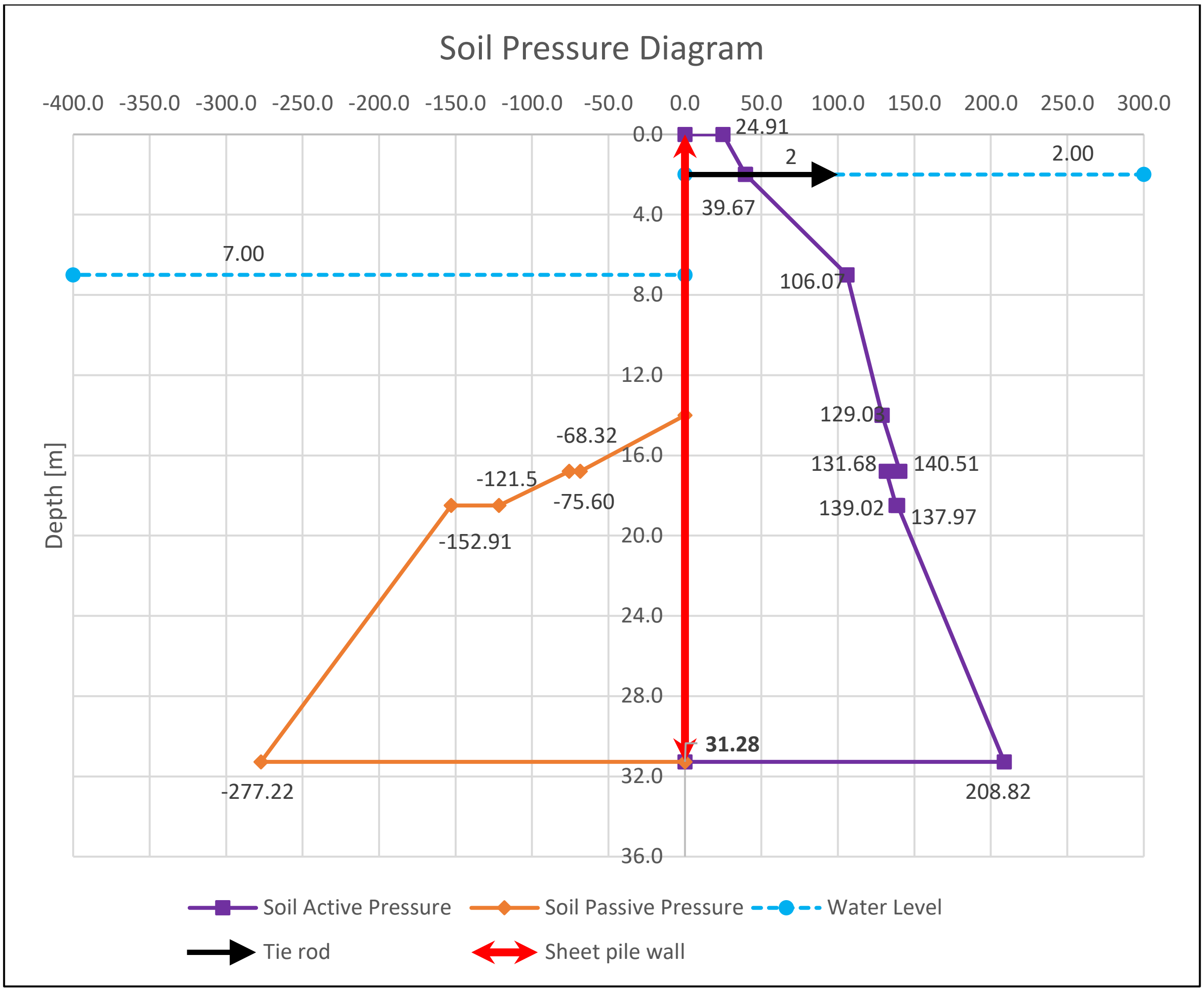

Figure 29: Soil Pressure Diagram with Sheet Pile Length

From the equilibrium of horizontal forces (Table 20 and Table 21), the force acting on the anchor (tie rod) can be calculated. This is done accordingly:

Horizontal forces from the active side:

$$\sum F_a = 2.73 \cdot x^2 + 139.05 \cdot x + 1859.29 \tag{6.17}$$

Horizontal forces from the passive side:

$$\sum F_p = 10.08 \cdot x^2 + 86.29 \cdot x + 263.18 \tag{6.18}$$

Equilibrium of horizontal forces:

$$\sum F_a = \sum F_p \tag{6.19}$$

The received square equation is:

$$\sum F_t = 7.35 \cdot x^2 - 52.76 \cdot x - 1595.11. \tag{6.20}$$

By replacing the $\boldsymbol{X = 12.775\ m}$ in equation (6.20) the force acting on the tie rod will be obtained:

$$F_t = 1069.47\ kN/m \tag{6.21}$$

For a sheet-pile wall that is supported by the use of an anchor, the active pressure will be divided differently from a wall without an anchor. The differences between the moments and forces depend upon the strength of the soil layers and from the stiffness of the wall. According to Jaanisoo (2016) [19], the experiments show, that for anchored sheet-pile walls usually the anchors are first to break or to give in. Practically never has the wall braked due to bending. That is why the forces acting on the anchor (tie rod) are taken 1.4 or 1.5 times greater than the calculated value. The bending moment of the wall may be reduced 30% for steel sheet-pile walls over 10m in length.[19]

Thus, the force acting on the anchor:

$$F_{t(1.5)} = 1069.47 \cdot 1.5 = 1604.20\ kN/m \tag{6.22}$$

The maximum bending moment is there, where the shear force is zero. In order to find the maximum bending moment, a table of shear forces was made. The shear forces are calculated by the differences of active and passive pressure as presented in Table 22.

Table 22: Calculated Shear Force Values for Finding the Maximum Bending Moment

No of Layer	σp,h (kPa)	σa,h (kPa)	Q (kN)	Depth (m)	Layer Thickness (m)
1(2a)		24.91	0.00	0	2
	Can	39.67	-64.58	2	
Tie Rod	1069.47		1004.89	2	
2(2a)		39.67	1004.89	2	5.00
		106.07	640.55	7.00	
3(2a)		106.07		7.00	7.00
		129.03	-182.28	14.00	
4(2a)	0.00	129.03		14.00	2.80
	68.32	140.51	-463.98	16.80	
5(2b)	75.60	131.68		16.80	1.70
	121.50	137.97	-525.64	18.50	
6(4b)	152.91	139.02		18.50	12.78
	277.22	208.82	0.00	31.28	

As can be seen from Table 22, the yellow coloured cells indicate that the shear force changes its sign from positive to negative in the third 3(2a) soil layer. Meaning, that the maximum bending moment from the top of the wall is:

$$l_M = \left(\frac{14.00 - 7.00}{-182.28 - 640.55} \cdot 640.55\right) - 7.00 = -12.45\ m \qquad (6.23)$$

Where,

$l_M - distance\ of\ the\ maximum\ bending\ moment\ from\ the\ top\ of\ the\ wall\ (m)$

The maximum shear force is near to the anchor with a value of:

$$Q_{max} \approx 1005\ kN/m \qquad (6.24)$$

The maximum bending moment is in the layer 3(2a). In order to find the maximum bending moment all the bending moment values before the depth $l_M = -12.45\ m$ are summed.

Table 23: Calculations of the Maximum Bending Moment

No of Layer	l (m)	Fa (kN/m)	Ma (kNm/m)	Fp (kN/m)	Mp (kN/m)
1(2a)	-11.45	49.82	-570.35		
	-11.12	14.76	-164.07		
2(2a)	-7.95	198.34	-1576.65		
	-7.12	166.00	-1181.25		
3(2a)	-1.95	742.47	-1447.31		
	-0.78	80.36	-62.89		
4(2a)					
5(2b)					
6(4b)					
Tie rod	10.45			1069.47	11175.18
		SUM	**-5002.53**		**11175.19**
		M_{max}	**6172.66**		

The maximum bending moment is $M_{max} = 6172.66\ kNm/m$ (Table 23). Like stated before, the corresponding value may be decreased by 30%. Thus, the steel sheet-pile wall has to be able to withstand the bending moment of:

$$\begin{aligned} M_d &= 0.7 \cdot M_{max} \\ &= 0.7 \cdot 6172.66 = 4320.86\ kNm/m \end{aligned} \tag{6.25}$$

Where,

$M_{max} - maximum\ bending\ moment\ (kNm/m)$

$M_d - calculated\ bending\ moment\ (kNm/m)$

6.5.1. Selection of the wall element

In order to determine the right profile of the steel sheet-pile wall, it is necessary to find the section modulus and based on that to choose a right element for the structure. As the bending moment calculated is quite high and the steel sheet-pile wall long, the steel grade was chosen higher S355 GP. Thus, the yield strength is: $f_{yk} = 355\ MPa$.

The section modulus can be calculated by the following formula:

$$\sigma = \frac{M_d}{W} \Rightarrow W = \frac{M_d \cdot \gamma_{M0}}{f_{yk}} = \frac{4320.86 \cdot 10^3 \cdot 1.0}{355} = 12171\ cm^3/m \tag{6.26}$$

Where,

$f_{yk} - yield\ strength\ (MPa)$

$\gamma_{M0} = 1.0 - partial\ factor\ for\ resistance$ [20]

$W - section\ modulus\ (cm^3/m)$

$\sigma - stress\ (MPa)$

The suitable steel sheet-pile profile was chosen from the product catalogue of ArcelorMittal [21] with a section modulus of $W = 12555\ cm^3/m$ (HZ 1180M D). The chosen element is a HZ/ AZ combination wall system. The wall is an economical system, which consist of HZ king piles, a pair of AZ sheet piles as intermediary element and special hot rolled connectors. On Figure 30 can be seen the sectional view of the chosen element.

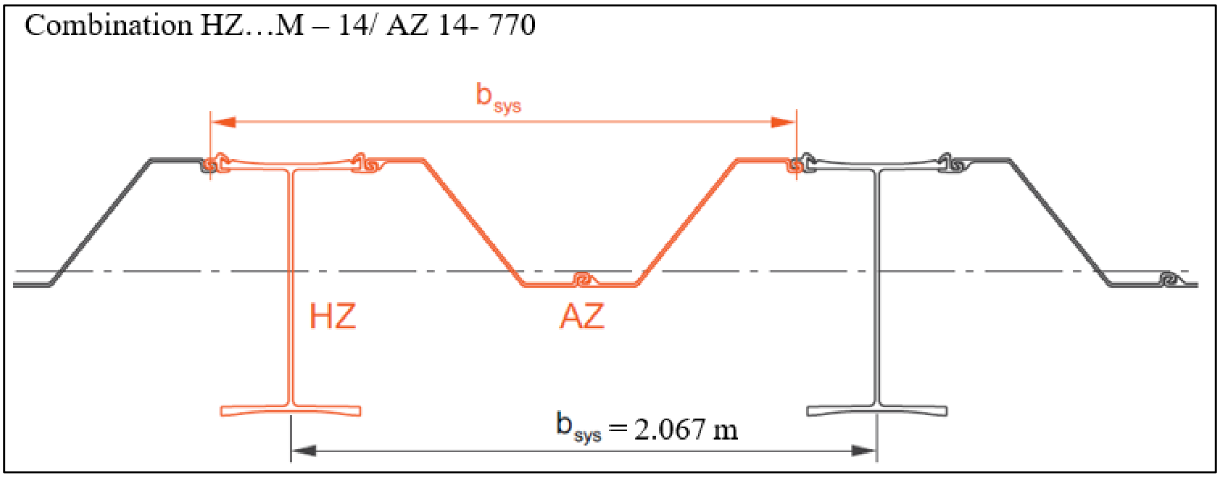

Figure 30: Chosen Steel Sheet-Pile Wall Section [21]
[http://ds.arcelormittal.com/repo/Unassigned/Docs/HZM-2014.pdf?flipbook=1]

As can be seen, the selected profiles section modulus is higher than the calculated and therefore fulfils the required strength criteria. However, the selected profile is just one of the suitable options. There is always a possibility to search for alternatives by choosing an element with higher/lower section modulus. Furthermore, the steel grade of the material can be selected higher, thus decreasing the section modulus and resulting maybe in a more economical solution. Finally, it is a decision of designers, engineers and the client – a teamwork of all the sides. In addition to, under this work, only one of the possible solutions is proposed.

6.5.2. Dimensioning of the anchor

The anchor is calculated as a centrally tensioned rod. From formula (6.22) the considered force acting on the anchor is $F_{t(1.5)} = 1604.20\ kN/m$. The step of the anchor is taken equal to $b_{sys} = 2.067\ m$ as presented on Figure 30. Thus, the force acting on one tie rod is found by the use of following formula:

$$F_{t(1)} = F_{t(1.5)} \cdot b_{sys} = 1604.20 \cdot 2.067 = 3315.88\ kN \qquad (6.27)$$

Where,

$F_{t(1)} - force\ acting\ on\ one\ anchor\ (kN)$

$F_{t(1.5)} - force\ acting\ on\ the\ anchot\ (kN/m)$

$b_{sys} - step\ of\ the\ anchors\ horizontally\ (m)$

The sectional area of the anchor can be found from the following formula [20]:

$$N_{pl,Rd} = \frac{A \cdot f_y}{\gamma_{M0}} \Rightarrow A = \frac{\gamma_{M0} \cdot N_{pl,Rd}}{f_y} \qquad (6.28)$$

$$= \frac{1.0 \cdot 3315.88 \cdot 10^3}{355} = 9340.50\ mm^2$$

For finding the radius of the tie rod:

$$r = \sqrt{\frac{A}{\pi}} = \sqrt{\frac{9340.50}{3.14}} = 54.5\ mm \qquad (6.29)$$

Where,

$N_{pl,Rd} - design\ platic\ resistane\ to\ normal\ forces\ of\ the\ cross-section\ (kN)$

$A -\ sectional\ area\ of\ the\ anchor\ (mm^2)$

$r - radius\ of\ the\ anchor\ (tie\ rod)(mm)$

$f_y - yield\ strength\ (MPa)$

$\gamma_{M0} = 1.0 - partial\ factor\ for\ resistance$ [20]

As can be seen from the result of (6.29), the radius of the tie rod has to be at least $r = 54.5mm$, thus the diameter of the rod must be not less than $d = 2 \cdot 54.5 = 109mm$.

On Figure 31 is presented how the tie rod would be connected to the steel sheet-pile wall.

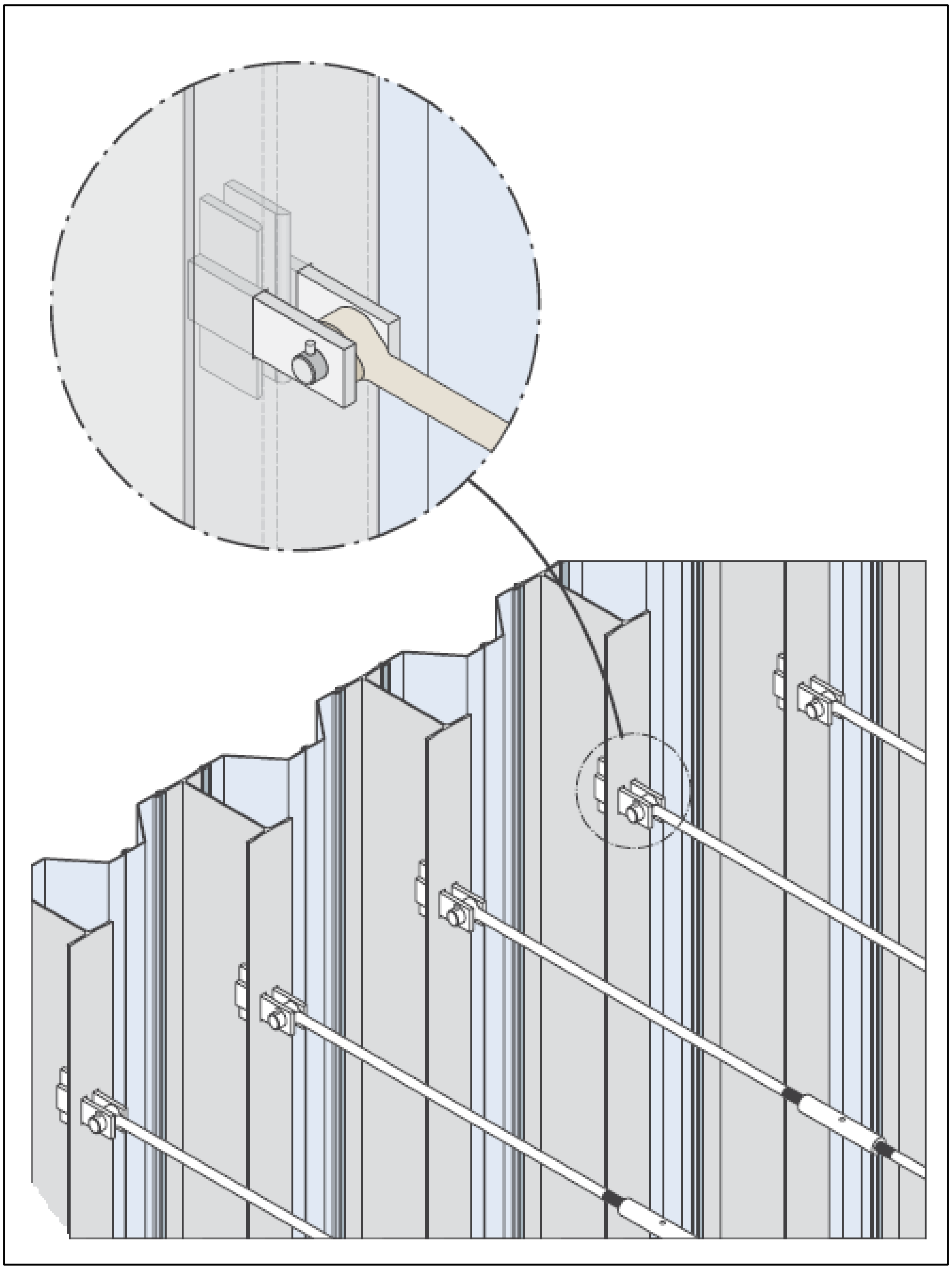

Figure 31: Connection of Tie Rod and Steel Sheet-Pile Wall [21]
[http://ds.arcelormittal.com/repo/Unassigned/Docs/HZM-2014.pdf?flipbook=1]

7. FLOATING DOOR

7.1. General

One of the goals within the framework of this thesis was to propose a suitable port entrance closing device for the A&R shipyard harbour in order to keep the water level constant during winter seasons and while launching new vessels or conducting docking operations.

According to the results of the multi-criteria analysis, all of the top scored layouts have a two entrance (gate) system for the harbour. The bigger gate, which is according to the top scored layout 48m long would be for the specific use of the shipyard and the smaller gate with a length of 20m for the marina users. However, as their concept of design would be the same only the longer gate will be studied here.

For the design of the floating door, the main criteria is to set boundaries of the water levels it has to work in and based on that define how much hydrostatic pressure it has to withstand. Here the water level difference considered was the same like for the cofferdam, meaning in the river side the SKN (LAT) value of -2.00m NN and in the harbour side the high water level (HWL) +3.00m NN. Those values represent the normal boundaries and were chosen in collaboration with the stakeholders. However, there are occasionally extreme cases, where the water level in the river drops even lower than the lowest astronomical tide (LAT=SKN) -2.00m NN or rises higher than the high water level considered here. In those extreme cases, the floating door still has to be in its place and withstand the water pressure. Meaning, if the hydrostatic pressure gets higher there has to be some kind of a pressure relief option or the scantling of the floating door has to be greater. Of course, the more secure option would be to have a greater scantling which on the other hand would result in a higher cost of the structure. Therefore, before making a final decision all cases have to be evaluated in order to achieve the most economical and safest design. Last but not least, under this framework the water level difference considered is 5m, having the lowest in the river side -2.00m NN (SKN) and the highest +3.00 NN (HWL) in the harbour side.

7.2. Type of gate

Hassani (1987) [22] Points out that the floating doors used to be the most popular closing device for dry docks in the U.S because of the following positive aspects:

- They have relatively low initial cost;
- They are reversible;
- The doors are mobile and relatively easy to handle;
- Can be easily replaced if necessary.

However, the negative sides can be listed as:

- The floating doors are slow in closing and opening;
- Uses considerable manpower and also may need help of tugboats;
- They depend on the shore utilities for their operation.

As one of the main considerations is the cost criteria and the fact that it should be relatively easy to use, the type of the gate chosen was a floating door that can be placed on its position with or without the help of tugboats. When on its place, the door will be flooded with water taken from the river with the use of internal or external pumps and submerged on its concrete foundation - by which the harbour will be sealed and making it independent from the river Weser tides.

Considering the aforementioned and taking into account the results obtained by the multi-criteria analysis, the best solution would be to have two floating gates. The smaller gate would be for the small pleasure craft users of the local Lemwerder yacht club and the bigger for the shipyard. That way the bigger gate can remain closed almost 95% of the time and needs to be only opened for maintenance and for accessing the harbour and syncrolift with big vessels. However, the smaller gate should remain open throughout the navigation season. The scantling of the structure as well the stability check was done only for the bigger floating door.

7.3. Scantling

The scantling of a structure generally refers to the dimensions of the different parts of the floating structure like plates, stiffeners, girders and frames. Here the scantling was done by following the Belgian Classification Society Bureau Veritas (BV) rules for harbour equipment.

In order to make the validation process of the designed preliminary floating door scantlings, the below BV rule was followed:

- NR612 – Rules for the Classification of Harbour Equipment – November 2015 edition. [23]

The secondary elements used were mainly bulb profiles, which were chosen from:

- NR217 – Rules for the Classification of Inland Navigation Vessels – November 2014 edition. [24]

Furthermore, as this preliminary design of floating door does not represent the total goal of the thesis and is just one part of the total work done, then in order to save time, the overall structural scantling was selected similar to the selected reference project done by a Belgian company DN&T S.A and checked by BV rules.

The scantling selected at first was not changed much as the goal is not the optimization of the floating door, but to have a general idea of the concept and its initial cost.

In Table 24 is brought out the general required input data for the calculations and under Table 25 can be seen the spacing and spans of the structural elements.

Table 24: General Input Data for BV rules

Description	**Abbreviation**	**Value**
Length overall	L_{OA}	48.00 m
Rule length	L	47.30 m
Breath	B	6.00 m
Depth	D	11.50 m
Draught	T	8.95 m
Construction material		Mild steel
Yield strength of the material	R_{eH}	235 MPa
Material factor	k	1.00

Table 25: Input Data for the Scantling of Plate, Ordinary Stiffener and Primary Supporting Members

Description	**Abbreviation**	**Value (mm)**
Spacing between frames	S_{fr}	2900.00
Span considered between frames	ℓ_{fr}	3275.00
Spacing between longitudinal primary elements	S_{lon}	1000.00
Span considered between longitudinal primary elements	ℓ_{lon}	2900.00
Spacing between vertical stiffeners	s_{vert}	500.00
Span considered between vertical stiffeners	ℓ_{vert}	1000.00

Based on the data provided in Table 24 and Table 25 calculations were made for the scantling.

7.3.1. Loading

In order to define the scantling of the considered structure, first one needs to define the loads present. Several assumptions and simplifications were made for defining the loads on the floating door:

1) There is no significant loading from the waves, as the floating door is situated in a river, 60 km inland from the North Sea coast. Therefore the waves generated on the river due to wind or storm are insignificant compared to the hydrostatic loading.
2) There is no hogging or sagging effect as we assume no waves.
3) The still water loads are neglected as those are considered vertically. The main load acting on the structure is assessed horizontally which is the hydrostatic pressure, resulted from the differences in water levels.
4) The structure is considered as simply supported, where the highest bending moment is acting in the middle of the structure and shear force is zero.

On the following Figure 32 can be seen an illustration of the floating door on its place with different water levels on both sides and the hydrostatic pressure acting on the structure.

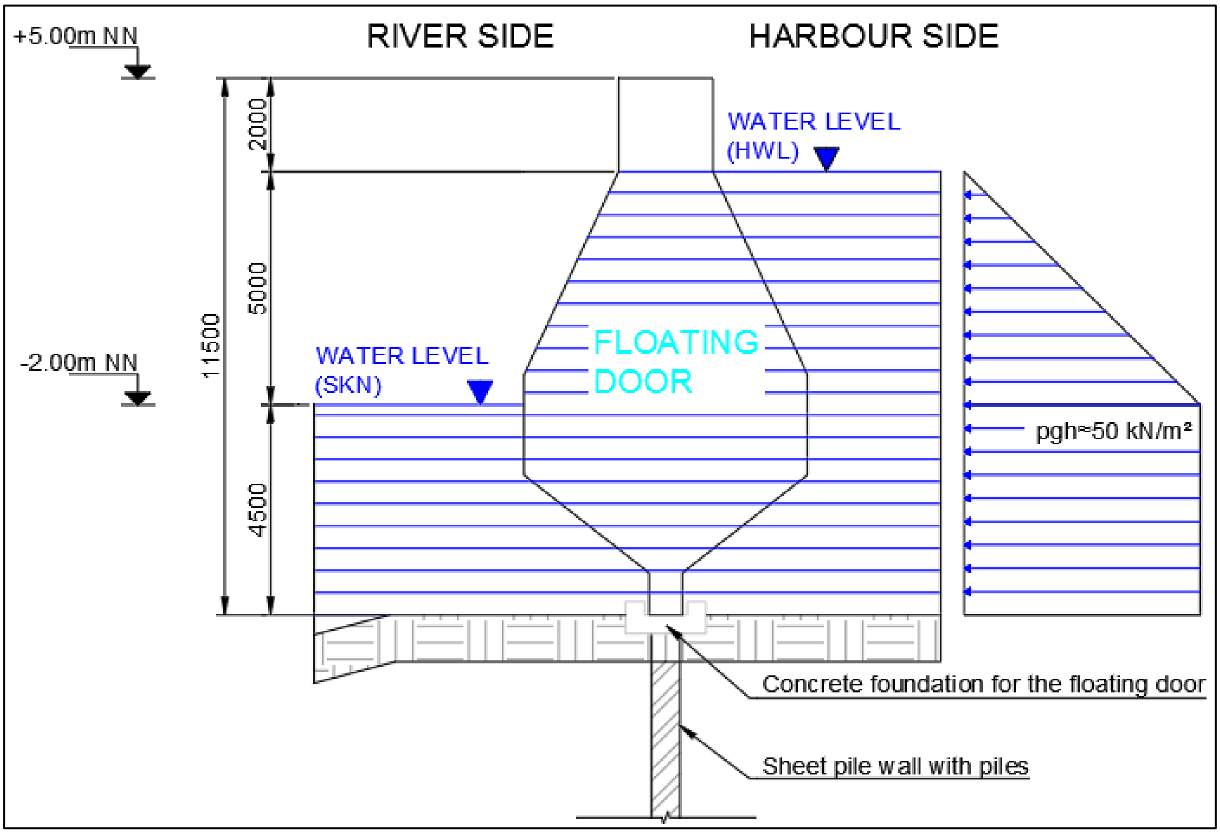

Figure 32. Floating Door on its Place and Filled with Water (HWL)

As can be seen from Figure 32, the difference between water levels is 5m. The hydrostatic pressure acting on the floating door is the highest when the door is in its place. The pressure is taken the same as in the calculations for sheet pile cofferdam.

Hydrostatic pressure:

$$p_H = \rho \cdot g \cdot h_d = 1.0 \cdot 9.81 \cdot 5 = 49.05\ kpa \approx 50\ kN/m^2 \quad (7.1)$$

Where,

$\rho - water\ density\ of\ fresh\ water\ (t/m^3)$

$g - acceleration\ of\ gravity\ (m/s^2)$

$h_d - differene\ between\ water\ levels\ (m)$

The design horizontal hull girder loads are determined by the use of BV rule NR612 – Part D – Chapter 3 – Section 1 (2.5.4):

- One side of the floating door subjected to a head of water h taken as:

$$h = T + 0.3m = 8.95 + 0.3 = 9.25\ m \tag{7.2}$$

Where,

$T - draught\ (m)$

- The line load considered on the longest side of the structure is:

$$q = p_H \cdot h = 50 \cdot 9.25 = 462.5\ kN/m \tag{7.3}$$

Where,

$p_H - hydrostatic\ pressure\ from\ the\ differences\ between\ water\ levels\ (kN/m^2)$

$h - head\ of\ water\ of\ one\ side\ of\ the\ floating\ door\ (m)$

- Fore and aft ends are assumed simply supported. The bending moment in the mid-section is:

$$M = \frac{q \cdot L^2}{8} = \frac{462.5 \cdot 47.3^2}{8} = 129.34 \cdot 10^3\ kNm \tag{7.4}$$

Where,

$q - line\ load\ considered\ acting\ on\ the\ structure\ (kN/m)$

$L - rule\ length\ (m)$

On Figure 33 can be seen a sketch of how the horizontal line load is considered to act on the structure.

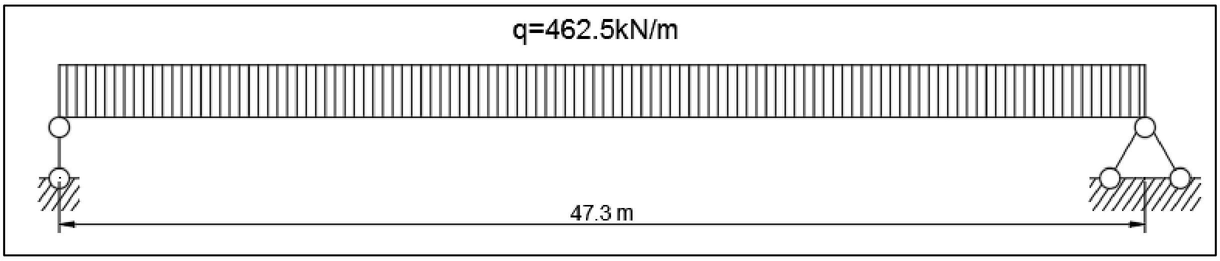

Figure 33: Line Load Acting on the Structure

After having defined the loads, deflection of the structure can be calculated by the following formula [17]:

$$\Delta = \frac{5 \cdot q \cdot L^4}{384 \cdot EI} = \frac{5 \cdot 462.5 \cdot 47.3^4}{384 \cdot 2.06 \cdot 10^8 \cdot 2.29} \approx 0.064\ m \tag{7.5}$$

Where,

$\Delta - deflection\ of\ the\ structure\ due\ to\ defined\ loads\ (m)$

$q - line\ load\ considered\ acting\ on\ the\ structure\ (kN/m)$

$L - rule\ length\ (m)$

$E - Young's\ modulus\ (kN/m^2)$

$I - second\ moment\ of\ inertia\ (m^4)$

As it can be seen from the result of (7.5) the deflection (Δ) of the structure is around 6.4cm.

After having defined the main loads, scantling of the structure can be done. As we deal here with a preliminary design phase, where the hoped outcome is the shape, weight and as the most important the initial cost of the structure, it shall be noted, that the stresses considered in order to define the scantling were taken the highest that act on the structure, not separately for each element.

7.3.2. Plating

The scantling of the plates is done by following BV rule NR612 – Part B – Chapter 4 – Section 2. The rules only provide the minimum plate thickness required for the considered structure. In Table 26 can be seen the scantling of the plates.

Table 26: Scantling of Plates

Description	Min Thickness Value by BV (mm)	Thickness Value Chosen (mm)
Keel plate	17.25	20.00
Bottom plate	12.94	15.00
Side shell plate	12.94	15.00
Upper side shell plate	8.19	12.00
Superstructure	-	8.00

It shall be noted, that for the calculations of the minimum plate thickness of all the compartments the value of internal pressure $P_C - pressure\ induced\ by\ carried\ liquids$ was used. However, as a simplification the total height of all the compartments was used in the calculations, not each compartments height separately.

7.3.3. Ordinary Stiffeners

The rulebook does not provide the dimensions of the elements, but only gives the minimum section modulus and the area of the cross-section. As the structure is transversally framed, the stiffeners there are also considered transversally. Like stated previously, the scantling of the structure was taken according to the reference project done by DN&T S.A. and checked with BV rules. The scantling of the ordinary stiffeners is done for the midship section.

Furthermore, the rulebook does not have specific guidelines for how to calculate the minimum section modulus of horizontal stiffeners on transversal bulkheads. Thus, to be able to validate the stiffeners there they are considered as ordinary transverse stiffeners.

In Table 27 can be seen the scantling of the ordinary stiffeners according to Bureau Veritas (November 2015) [23].

Table 27: Scantling of Ordinary Stiffeners

Element	**Profile**	**Min Section Modulus by BV (cm^3)**	**Min Sectional Area by BV (cm^2)**	**Final Dimensions of the Element (mm)**	**Final Section Modulus (cm^3)**	**Final Sectional Area (cm^2)**
Side frame	P	20.70	1.21	160 x 9	129.90	24.47
Horizontal Stiffeners on Transverse Bulkhead	P	131.23	5.16	180 x 8	151.90	18.90

The acquired value of minimum section modulus of the horizontal stiffeners on the transverse bulkhead by the rules increases because the span is taken $\ell = 3m$ which plays an important role in the formula given in the rulebook.

7.3.4. Primary Supporting Members

The scantling of primary members is done for the midship section. Both the longitudinal and transverse members are calculated considering attached plating.

Table 28: Scantling of Primary Members

Element	Profile	Min Section Modulus by BV (cm^3)	Min Sectional Area by BV (cm^2)	Final Dimensions of the Element (mm)	Final Section Modulus (cm^3)	Final Sectional Area (cm^2)
Longitudinal members	T	1523.07	33.61	220 x 15 + 120 x 15	2631.68	201.00
Transverse members	T	1212.11	33.16	220 x 15 + 120 x 15	1479.32	126.00

For understanding better the concept and have a greater overview of the structure a 3D model was created in the software Solidworks to express the structural arrangements of the floating door. On Figure 34 can be seen a picture of the 3D model. Final drawings of the hull scantling can be found in APPENDIX IV.

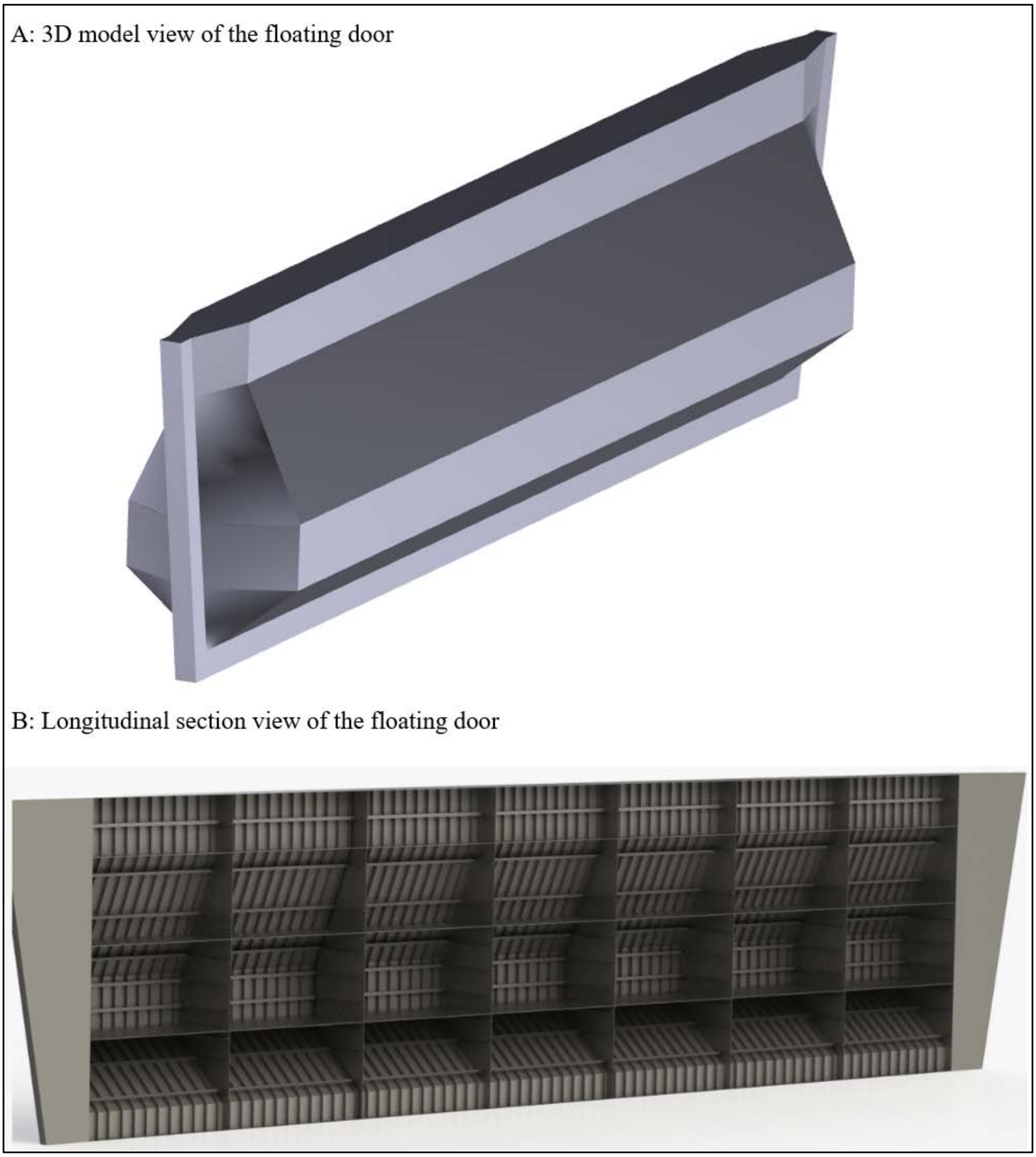

Figure 34: Model and Longitudinal Sectional View of the Floating Door

7.4. Weight Estimation and Centre of Gravity

The weight estimation is essential to the design calculations like the design draft, stability and seakeeping. As the floating door is symmetrical, the longitudinal centre of gravity (LCG) is in the middle of the floating door. For this kind of structure, the most important is the transverse centre of gravity (TCG) and vertical centre of gravity (VCG). In order to have the floating door stable, the centre of gravity (CG) needs to be as low as possible.

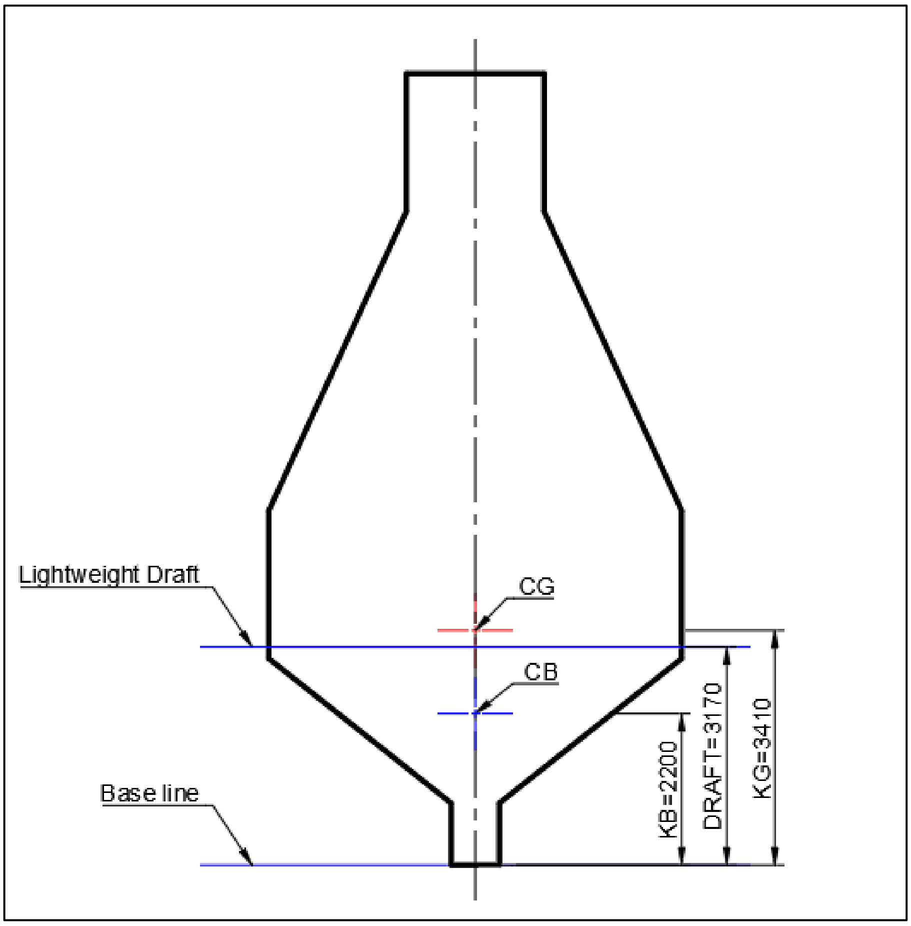

Figure 35: Centre of Gravity

An important thing to point out here is that all the distances are measured from x, z and y-axis. LCG is measured from the aft perpendicular (x-axis), VCG from the base line or from the keel line (z-axis) and TCG is measured from the centre line (y-axis).

According to the rules, the metacentric height (GM) has to remain positive in all loading conditions. This can be achieved by having a solid keel with ballast weight (for example concrete) or by having the scantling of the bottom structure higher. In this preliminary project, both possibilities were used to have the centre of gravity as low as possible in order to have the floating door stable.

Based on the scantling of the structure the total lightweight of the structure can be computed. For the lightweight calculations only the structural part was considered. The VCG is taken from AutoCad. The weight estimation can be seen in detail in APPENDIX V.

The total lightweight estimated is around 380 tons. The KG value, which is taken from the bottom of the solid keel (Base line) until the centre of gravity is KG = 3.41 m. The total ballast water weight estimated is around 1474.9 tons. In Table 29 can be seen the total weight estimated.

Table 29: Weight Estimation

Description	**Abbrev.**	**Amount**	**Unit**
Total lightship weight estimated (only structure):	$W_{L,T}$	380.0	t
Total weight of ballast water with full tanks:	$W_{b,T}$	1474.9	t
Total weight of floating door when in its place:	W_T	1854.9	t

7.5. Stability

After computing the lightweight of the floating door based on the defined scantling, stability check could be performed. Based on BV rules [23], following criteria have to be met:

- The metacentric height GM must remain positive in all loading conditions;
- All calculations are to be carried out free from trim and sinkage.

The most problematic condition for achieving positive GM was with lightship condition, where there is no ballast water. If the weight of the door increases due to ballast water, the structure will become more stable as the centre of gravity goes down, resulting in the increase of GM (Table 30).

Several attempts were done by modifying the shape, scantling and solid keel in order to finally achieve positive stability without ballast water. The stability check was done using the computer program Maxsurf Stability.

Table 30 indicates that the draft of the lightship is 3.17 m. Moreover, the floating door reaches its full draft, which is 9.5m, at a total weight of 1678 tons. Meaning, that with 1298 tons of ballast water in the tanks the floating door has achieved its designed draft and is set on its designed concrete foundation.

Table 30: Stability Check from the Software Maxsurf

Draft Amidship	3.17	4.41	5.66	6.37	7.19	8.20	9.5	*11.46**
Displacement t	380.00	707.80	1036.00	1199.00	1363.00	1527.00	1678.00	*1855.00*
WL Length m	45.10	45.53	45.97	46.22	46.50	46.85	47.30	*47.99*
Beam max extents on WL m	6.00	6.00	5.53	4.87	4.12	3.20	2.00	*2.00*
Wetted Area m^2	419.80	532.43	651.74	723.28	806.28	908.73	1042.22	*1228.64*
Waterpl. Area m^2	256.92	258.24	238.79	211.05	178.84	139.06	87.83	*88.58*
KB m	2.20	2.93	3.60	3.93	4.27	4.63	5.01	*5.53*
KG m	3.41	3.41	3.41	3.41	3.41	3.41	3.41	*3.41*
BMt m	2.03	1.09	0.58	0.35	0.18	0.08	0.02	*0.02*
BML m	106.19	57.92	36.90	28.29	21.21	14.80	8.67	*8.06*
GMt m	0.81	0.61	0.77	0.86	1.04	1.30	1.62	*2.14*
GML m	104.98	57.45	37.08	28.81	22.07	16.03	10.272	*10.18*
KMt m	4.22	4.02	4.18	4.27	4.45	4.71	5.026	*5.55*
KML m	108.39	60.86	40.49	32.22	25.48	19.44	13.682	*13.59*

** According to the current design and used boundaries the draft of 11.46m is not possible. It serves only as an insight that if the ballast tanks would be 100% filled the draft reached would correspond to the value indicated. The maximum loading case corresponds to the draft of 9.5m.*

As it can be observed from the results, the floating door tanks have more capacity that is actually required. Meaning, that there is around a 10-12% buffer of the tanks and the floating door does not require 100% full ballast water for achieving its designed draft of 9.5m. The draft of *11.46m** serves as an insight, that if there would be no foundation to met and the ballast tanks would be 100% filled, such draft can be reached – meaning, the capacity of the tanks is more than actually required. However, as the draft of *11.46m** corresponds to the extreme case, it is out of the previously established boundaries in section 7.1 and is therefore not studied further here. Though, for achieving exact results one should go back to the beginning and start optimizing like the design spiral indicates.

Nevertheless, the goal of having a preliminary floating door design, with good structural arrangement, enough scantling and stability has been achieved.

7.6. Alternative Solution for Floating Door

The concept of the floating door is relatively old and has been used widely all over the world as a gate for dry docks and navigation locks. However, with time passing by there have come up some new possibilities. One of those possibilities is an inflatable rubber gate. They are relatively new type of gates and are considered as innovative hydraulic structures. The basic concept of the inflatable rubber gate is that the rubber body will be filled by pumping in air or water until it reaches its design draft or allowable pressure and by that sealing the waterway. If the waterway needs to be freed again, the air or water inside the rubber body is allowed to escape by that deflating the rubber body. Though, that sort of gates usually are used at hydropower plants as a dam, it is also possible to use them instead of standard steel gates in navigation channels. [25]

In the report of Inflatable Structures in Hydraulic Engineering by PIANC-WG166 (2016) [25] following advantages over standard steel gates have been pointed out:

- Capital and maintenance costs are lower than that of the steel gates. It is because the structure is flexible and easy to use;
- There are no moving parts such as hinges or bearings. There is no problem with corrosion and with sealing. It is more environmentally friendly as there is no need to use any lubricants;
- There are less mechanical parts as there are no drive mechanisms such as hydraulic cylinders, electrical chains or actuators;
- The inflatable rubber gate is safe to operate, as it is always possible to inflate or deflate them fast;
- There is no need for the assistance of tugboats compared to e.g. floating door;
- In case of damage or regular maintenance, the rubber membrane of the inflatable gate can be replaced within few weeks, resulting in far less construction time.

As could be seen from the out stated points, the alternative solution of an inflatable rubber gate instead of the proposed floating door would mean for A&R that there is less manpower needed to operate the gate, there is no need for the assistance of tugboats, it is probably more comfortable to use and would be cheaper.

However, there are also some negative points:

- There is very less experienced suppliers and manufactures of this kind of structure;
- Rubber is a very complex material that acquires special attention. For example the recipe of the rubber or the joining places of rubber;
- The production, construction, installation and maintenance requires very skilled personnel.

Furthermore, one of the possible applications of the inflatable rubber gate for the A&R shared harbour would be to have it instead of the smaller entrance gate that is designed for the marina users, as this gate has to remain open throughout the navigation season. Hence, it gives the possibility to close the harbour entrance safely and fast when there is a danger of storms, extreme tidal circumstances or some sort of other danger to the harbour basin. On Figure 36 is presented an example of a water-filled inflatable rubber gate.

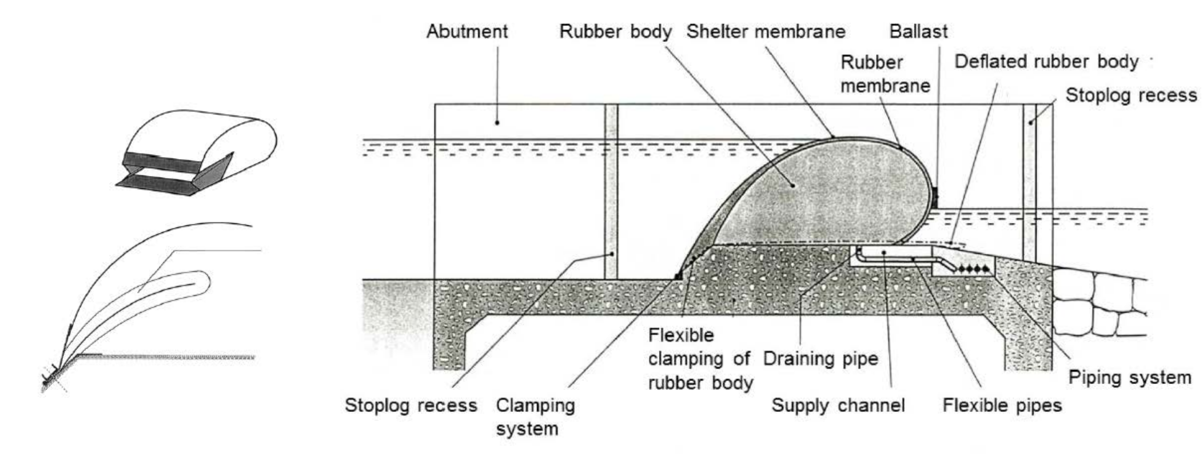

Figure 36: Cross-Section of a Water-Filled Inflatable Rubber Gate.
(Available: PIANC-WG166 (2016) [25], page 28)

8. APPROXIMATE COST

The cost estimation of the layouts is done for the top four scored layouts that turned out in the multi-criteria analysis. The information about the cost of sheet piles, installation and backfilling was received by communicating with *SHI Planungsgesellschaft mbH*. It is a civil engineering company that has done previously some co-work with A&R. The steel price per tonnage for the floating door(s) was obtained from *Abeking & Rasmussen*. The prices for the floating marina elements was received from a floating marina designer, manufacturer and installation company *Top Marine OÜ*. The prices have been obtained from different sources and have to be taken as rough numbers.

The cost estimation analysis of the layouts does not contain the cost estimation of the concrete foundation for the floating door(s) neither for the sealed perimeter nor the required dredging or the anchorage of the pontoons in the floating marina. From Table 32 on page 100 can be seen the approximate cost estimation of the four best layouts.

On Table 31 can be seen, that the cheapest would be the 2. Layout (6C) and the most expensive 3. Layout (3D). The difference between the cheapest and the most expensive layout is around 16.9 %.

Table 31: Estimated Cost of the Layouts

Layout	**Estimated cost**
2. Layout (6C)	9,396,400.00 €
1. Layout (6D)	9,485,400.00 €
4. Layout (8D)	9,991,260.00 €
3. Layout (3D)	11,300,790.00 €

Table 32: Cost Estimation of the Top Scored Layouts

Layouts listed by the results of MCA:			**1. Layout (6D)**		**2. Layout (6C)**		**3. Layout (3D)**		**4. Layout (8D)**	
	Price	Unit	Quantity	Total	Quantity	Total	Quantity	Total	Quantity	Total
Boat Pontoon with plastic floats	3,000.00 €	pc	69.00	207,000.00 €	36.00	108,000.00 €	72.00	216,000.00 €	72.00	216,000.00 €
Mooring fingers	2,000.00 €	pc	44.00	88,000.00 €	51.00	102,000.00 €	46.00	92,000.00 €	46.00	92,000.00 €
Installation	1,000.00 €	day	18.00	18,000.00 €	14.00	14,000.00 €	21.00	21,000.00 €	21.00	21,000.00 €
Floating Marina			**313,000.00 €**		**224,000.00 €**		**329,000.00 €**		**329,000.00 €**	
Sheet pile, anchoring, penetration with floating equipment	20,000.00 €	m	338.00	6,760,000.00 €	338.00	6,760,000.00 €	434.00	8,680,000.00 €	359.00	7,180,000.00 €
Backfill	50.00 €	m^3	15848.00	792,400.00 €	15848.00	792,400.00 €	17215.80	860,790.00 €	17245.20	862,260.00 €
Steel Sheet-Pile Cofferdam			**7,552,400.00 €**		**7,552,400.00 €**		**9,540,790.00 €**		**8,042,260.00 €**	
Steel	1,000.00 €	ton	160.00	160,000.00 €	160.00	160,000.00 €	160.00	160,000.00 €	160.00	160,000.00 €
Labour	2,000.00 €	ton	160.00	320,000.00 €	160.00	320,000.00 €	160.00	320,000.00 €	160.00	320,000.00 €
Floating Door (small)			**480,000.00 €**		**480,000.00 €**		**480,000.00 €**		**480,000.00 €**	
Steel	1,000.00 €	ton	380.00	380,000.00 €	380.00	380,000.00 €	317.00	317,000.00 €	380.00	380,000.00 €
Labour	2,000.00 €	ton	380.00	760,000.00 €	380.00	760,000.00 €	317.00	634,000.00 €	380.00	760,000.00 €
Floating Door (big)			**1,140,000.00 €**		**1,140,000.00 €**		**951,000.00 €**		**1,140,000.00 €**	
TOTAL			**9,485,400.00 €**		**9,396,400.00 €**		**11,300,790.00 €**		**9,991,260.00 €**	

9. COMPARISON

By comparing the approximate costs from the Table 32 on page 100, it is visible that the cost of the 2.Layout (6C) is the smallest. This, however, depends on the floating marinas cost, as there are fewer pontoons compared to 1.Layout (6D). The highest cost would be of the 3.Layout (3D) which is around 16% more expensive than the top scored 1.Layout (6D) by the multi-criteria analysis. The top scored layout ranks according to multi-criteria analysis compared to the results of the cost estimation analysis are presented in Table 33.

Table 33: Comparison of Layout Ranks According to Different Analysis

Rank	Multi-criteria analysis results	Cost estimation analysis results
1.	Layout (6D) - 7.69p	Layout (6C) - 9,396,400.00 €
2.	Layout (6C) - 7.60p	Layout (6D) - 9,485,400.00 €
3.	Layout (3D) - 7.55p	Layout (8D) - 9,991,260.00 €
4.	Layout (8D) - 7.52p	Layout (3D) - 11,300,790.00 €

As it may be observed from the above table, according to cost estimation layout (6D) and (6C) switch places and also layout (3D) and (8D) switch places. However, as layout (8D) sheet pile wall reaches to the navigation channel, it may face some complications with the authorities or other unforeseen problems that will have an impact on the budget as well as approval time for the implementation of the layout (8D). Therefore layout (8D) should be viewed more critically.

From Table 33 also can be seen why it was decided not to use the cost criteria in the multi-criteria analysis (MCA) as this criterion surely would have an impact on the outcome and probably not represent the most beneficial layout by its functionality.

10. CONCLUSIONS AND SUGGESTIONS

The purpose of this thesis turned out to be relevant when the first 100m superyacht by Abeking & Rasmussen was launched by the use of the barge. As the shared harbour in its current state is too much influenced by the tides in the river Weser it made the launching operation very complicated and risky. Moreover, the entrance width and location of the harbour do not benefit the manoeuvrability of big vessels. As there are surely more 100m or longer superyachts orders coming in, it rose a necessity for looking ways of how to redesign the shared harbour in a way that would benefit the two stakeholders A&R and the local Lemwerder Yacht club.

By means of finding a consensus between the stakeholders, an investigation of different layout possibilities for Abeking & Rasmussen shipyard shared harbour was done in terms of having the option of keeping constant water level inside the harbour for conduction more efficiently the launching/ docking operations, having better manoeuvrability possibilities with big vessels and decrease the need for dredging the basin. As the harbour is shared, many constraints and different objectives had to be taken into account. Thus, a multi-criteria assessment analysis was performed for determining the best layout solutions.

By determining the best layouts that finally benefit both of the stakeholders, a more detailed design, relevant calculations for the major parts and cost estimation analysis was performed for the top four scored layouts. The water level boundaries for calculating the structure of the cofferdam and floating door are defined in their respective chapters.

Furthermore, it still may seem that it only benefits the shipyard itself by closing the harbour for the winter period. But on the contrary, as a result of literature analysis done for the lower Weser region, it comes out that there is a possibility to avoid up to 57% of sedimentation coming into the harbour and by that also decreasing the need for dredging immensely in the basin.

What is more, the layouts with the two gate system performed the best in the multi-criteria analysis (MCA). The two gate systems mean, that there would be one floating door designed for the marina users and one bigger floating door for the use of the A&R shipyard. This, however, gives the chance to decrease the harbour entrance of the marina users, which also will have a decreasing effect on the sedimentation coming in and finally serves better as a protecting barrier for the marina and the small crafts there. Besides, the bigger gate would remain closed unless there is a launching/docking operation coming up.

In addition to, one of the goals of the local Yacht Club is to have more and bigger boat places. This was achieved, however, as the harbour territory is quite limited, there is not space endlessly. Nevertheless, according to the author opinion, the floating marina right now is not well distributed, resulting finally in a non-effective use of the space in the marina.

Last but not least, the new entrance for the shipyard is designed so, that without much effort a vessel launched by the syncrolift could leave the harbour – meaning far fewer manoeuvres inside the harbour basin and avoiding turning angles of 90 degrees. However, for vessels, that need to be launched by the use of barge, the floating marina still has to be dismantled, at least partially. Anyhow, the barge by which the vessels would be launched can enter the harbour with much less effort by conducting less risky manoeuvres. Not to mention, the launching operations of vessels by barge or syncrolift can be done independently from the river Weser tides.

Finally, taking into account the various different parts to consider in this master thesis and the results obtained, it can be stated that the goal was achieved by resulting in a new harbour layout solutions that would benefit both of the stakeholders.

As a suggestion for future work, it would be worth to consider to design the cofferdam and floating door so, that the water level would be held around 0.00m NN when the harbour is closed. That way the difference in water levels would be less and the loads on the cofferdam as well as on the floating door would be reduced, resulting finally in a more economical design. Moreover, it is definitely worth to investigate the alternative solution for the floating door such as the proposed inflatable rubber gate. To use this system as a replacement for the smaller entrance gate would definitely uphold some benefits, like better protection against storms and floods during navigation season. However, the use of the inflatable rubber gate at the bigger entrance is more questionable, as it would have to remain closed 95% of the time.

To sum up, A&R has existed over 100 years, passed by for generations, overcoming several difficulties such as economic crises, floods, fires and wars it still has evolved further by keeping up with the client's expectations and markets demands. The same can be told to the local Yacht Club that has existed there along with Abeking & Rasmussen. Maybe it is their coexistence that finally pushes them to their limits and develop further for keeping up with the changes over time, by making history together.

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APPENDIX I

The table on the following page in A3 format.

Table 34: Long Term Mean Freshwater Runoff Values

Long Term Mean Freshwater Runoff (MQ) [m^3/s]															
Nr	**Year**	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**Monthly Average**	**Total Annually**
1	1980	281	708	297	412	276	251	512	263	251	198	201	411	338	4061
2	1981	627	622	1050	452	331	538	387	391	273	379	259	417	477	5726
3	1982	799	630	555	367	341	214	173	155	133	159	485	798	401	4809
4	1983	439	492	455	804	486	318	185	145	136	132	164	268	335	4024
5	1984	446	620	272	314	328	549	253	194	282	355	130	231	331	3974
6	1985	334	462	296	408	291	258	240	187	176	157	359	384	296	3552
7	1986	717	350	412	676	325	344	179	149	170	197	156	314	332	3989
8	1987	1010	659	807	666	331	432	262	287	277	255	211	295	458	5492
9	1988	572	648	1030	817	292	226	209	156	154	163	403	486	430	5156
10	1989	388	321	446	306	211	146	129	126	129	138	173	595	259	3108
11	1990	319	445	638	269	186	152	124	107	149	124	264	322	258	3099
12	1991	604	246	283	200	157	139	130	115	89.1	97.8	207	293	213	2560.9
13	1992	380	287	505	411	237	178	139	122	125	146	359	505	283	3394
14	1993	672	542	347	285	194	164	148	189	219	322	231	688	333	4001
15	1994	1270	707	918	936	401	291	191	165	224	182	350	414	504	6049
16	1995	765	1230	636	645	340	315	195	143	173	183	188	195	417	5008
17	1996	166	284	237	197	184	144	133	120	115	186	340	397	209	2503
18	1997	226	471	562	335	286	172	193	148	124	135	138	241	253	3031
19	1998	379	221	483	348	268	206	173	144	279	551	1210	618	407	4880
20	1999	570	728	807	454	270	202	162	147	128	146	147	343	342	4104
21	2000	370	631	928	378	214	160	162	152	151	146	167	196	305	3655
22	2001	335	484	473	479	263	191	153	129	230	222	238	474	306	3671
23	2002	518	923	860	374	541	286	421	393	228	305	749	497	508	6095
24	2003	1220	584	472	280	216	169	134	109	119	139	128	213	315	3783
25	2004	424	594	315	268	351	169	186	149	158	161	296	298	281	3369
26	2005	437	612	471	347	300	179	145	159	130	137	145	278	278	3340
27	2006	251	351	422	597	285	275	146	162	139	135	174	185	260	3122
28	2007	510	521	652	284	248	285	251	351	290	489	568	730	432	5179
29	2008	636	622	632	585	277	194	179	178	134	167	189	238	336	4031
30	2009	209	339	624	332	199	150	145	114	112	161	261	414	255	3060
31	2010	411	366	706	380	252	206	123	184	251	245	459	414	333	3997
32	2011	931	504	281	214	151	137	142	130	136	137	107	278	262	3148
33	2012	757	334	276	189	151	147	184	127	112	137	137	333	240	2884
34	2013	408	531	333	273	347	595	185	136	143	168	261	270	304	3650
35	2014	297	272	190	150	186	174	203	198	164	202	189	302	211	2527
Monthly Average Runoff of Fresh Water of 35 Years [m3/s]		534	524	533	412	278	244	196	175	174	204	287	381	329	3944
Seconds in one month		2678400	2419200	2678400	2592000	2678400	2592000	2678400	2678400	2592000	2678400	2592000	2678400	2628000	31536000
Monthly Average Runoff of Fresh Water of 35 Years [m3/mon]		1429347291	1267729920	1428811611	1068792686	743523840	633632914	526190811	468643474	451978149	547679232	743755886	1020470400	860879685	10330556215
Monthly Average SPM Volume in the Freshwater Runoff of 35 Years [m3/mon]		47645	42258	47627	35626	24784	21121	17540	15621	15066	18256	24792	34016	28696	344352

APPENDIX II

Table 35: Grading System of Sub-Criteria's for Main Criteria

Criteria	Sub-Criteria (parameters to consider)		
Entrance of the harbour	**1) Width of the harbour entrance for A&R vessels;**		
	Grade	**Explanation**	
	A	Excellent	≥ 50m
	B	Good	46…< 50m
	C	Satisfactory	43…< 46m
	D	Poor	40…< 43m
	E	Bad	< 40m
	2) The harbour entrance location impact on the shipping traffic;		
	Grade	**Explanation**	
	A	No impact on traffic	
	B	Low impact on traffic	
	C	Moderate impact on traffic	
	D	High impact on traffic	
	3) Necessity of a secondary entrance for the marina user;		
	Grade	**Explanation**	
	A	No need- or the location and the width of the 2nd entrance is good;	
	B	Moderate- or the location and the width of the 2nd entrance can be better;	
	C	High Need- or the location and the width of the 2nd entrance is not good and can create safety risks;	
	4) The size of the vessels that can access the harbour (for example, if a 125 m vessel can access the harbour);		
	Grade	**Explanation**	
	1	< 85m	
	2	85…< 90m	
	3	90…< 95m	
	4	95…< 100m	
	5	100…< 105m	
	6	105…< 110m	
	7	110…< 115m	
	8	115…< 120m	
	9	120…< 125m	
	10	≥ 125m	
Maneuverability inside the harbour basin	**1) Floating marina influence on the launching of A&R vessels by barge;**		
	Grade	**Explanation**	
	A	No influence	
	B	Low influence	
	C	Moderate influence	
	D	High Influence	
	2) Accessibility of the synchrolift (for example, if a vessel with a length of 90m can access the synchrolift);		
	Grade	**Explanation**	
	A	Excellent	≥ 95m
	B	Good	90…< 95m
	C	Satisfactory	85…< 90m
	D	Poor	80…< 85m
	E	Bad	< 80m
	3) Moving and rotation possibilities inside the harbour basin in terms of space and safety;		
	Grade	**Explanation**	
	A	Good possibilities	
	B	Moderate possibilities	
	C	Poor possibilities	

Criteria	Sub-Criteria (parameters to consider)							
Time to release a ship	**1) Time to launch a vessel by barge (with closed gate);**							
	Grade	**Hours/days**						
	1	> 10days						
	2	≤ 10days						
	3	≤ 8days						
	4	≤ 6days						
	5	≤ 4days						
	6	≤ 3days						
	7	≤ 48h						
	8	≤ 36h						
	9	≤ 24h						
	10	≤ 12h						
	2) Time to launch a vessel by synchrolift (with closed gate);							
	Grade	**Minues/hours**						
	A	< 45min						
	B	45min... < 1h						
	C	1h... < 1h 15min						
	D	1h 15min… < 1h 30min						
	E	≥ 1h 30min						
Effect of tides/ currents/ sedimentation	**1) Accessibility of the harbour during high or low tide during navigation season;**							
	Grade	**Explanation**						
	A	Good accessibility						
	B	Moderate						
	C	Poor accessibility						
	2) During navigation season, tide caused currents inside the harbour basin;							
	Grade	**Explanation**						
	A	Low current						
	B	Moderate current						
	C	High current						
	3) Sedimentation transport inside the harbour basin or to the entrance;							
	Grade	**Explanation**						
	A	Low sediment transportation						
	B	Moderate						
	C	High sediment transportation						

Criteria	Sub-Criteria (parameters to consider)							
Impact on the marina and its users	**1) Number of boat place;**							
	Grade	**Boat places**						
	1	65…< 70						
	2	70…< 75						
	3	75…< 80						
	4	80…< 85						
	5	85…< 90						
	6	90…< 95						
	7	95…< 100						
	8	100…< 105						
	9	105…< 110						
	10	≥110						
	2) Accessibility of floating pontoons by land and river;							
	Grade	**Explanation**						
	A	Good accessibility						
	B	Moderate						
	C	Poor accessibility						
	3) Width of the fairways between floating docks and berthing places;							
	Grade	**Explanation**						
	A	Good						
	B	Moderate						
	C	Poor						
	4) Accessibility of the slipway with pleasure crafts;							
	Grade	**Explanation**						
	A	Excellent		≥ 15m				
	B	Good		12…< 15m				
	C	Satisfactory		10…< 12m				
	D	Poor		8…< 10m				
	E	Bad		< 8m				
	5) Future possibilities for having more and/or bigger boat places (for example: min size of boats 9m);							
	Grade	**Explanation**						
	A	Great future possibilities						
	B	Moderate possibilities						
	C	Low possibilities						
	D	No possibilities						
Complexity of the solution and need of public authorisation	**1) Complexity of the solution;**							
	Grade	**Explanation**						
	A	Low complexity						
	B	Moderate complexity						
	C	High complexity						
	2) Need of public approval in case of harbour extension into the river channel;							
	Grade	**Explanation**						
	A	Small or no need of public approval						
	B	Little need of public approval, but the process is not so complicated						
	C	Large need of public approval						

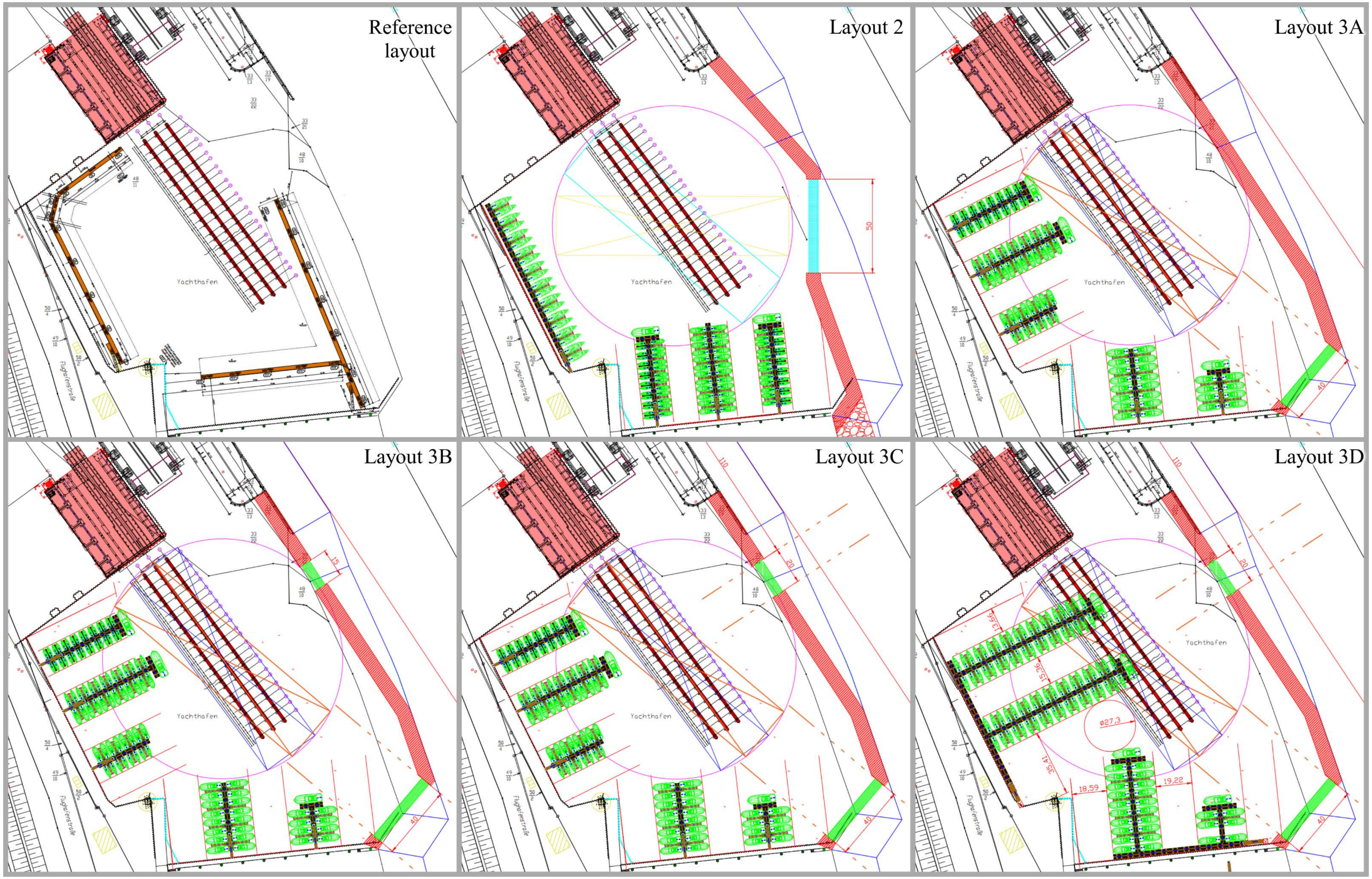


Figure 37: Reference Layout and Brainstormed Layouts 2-3D

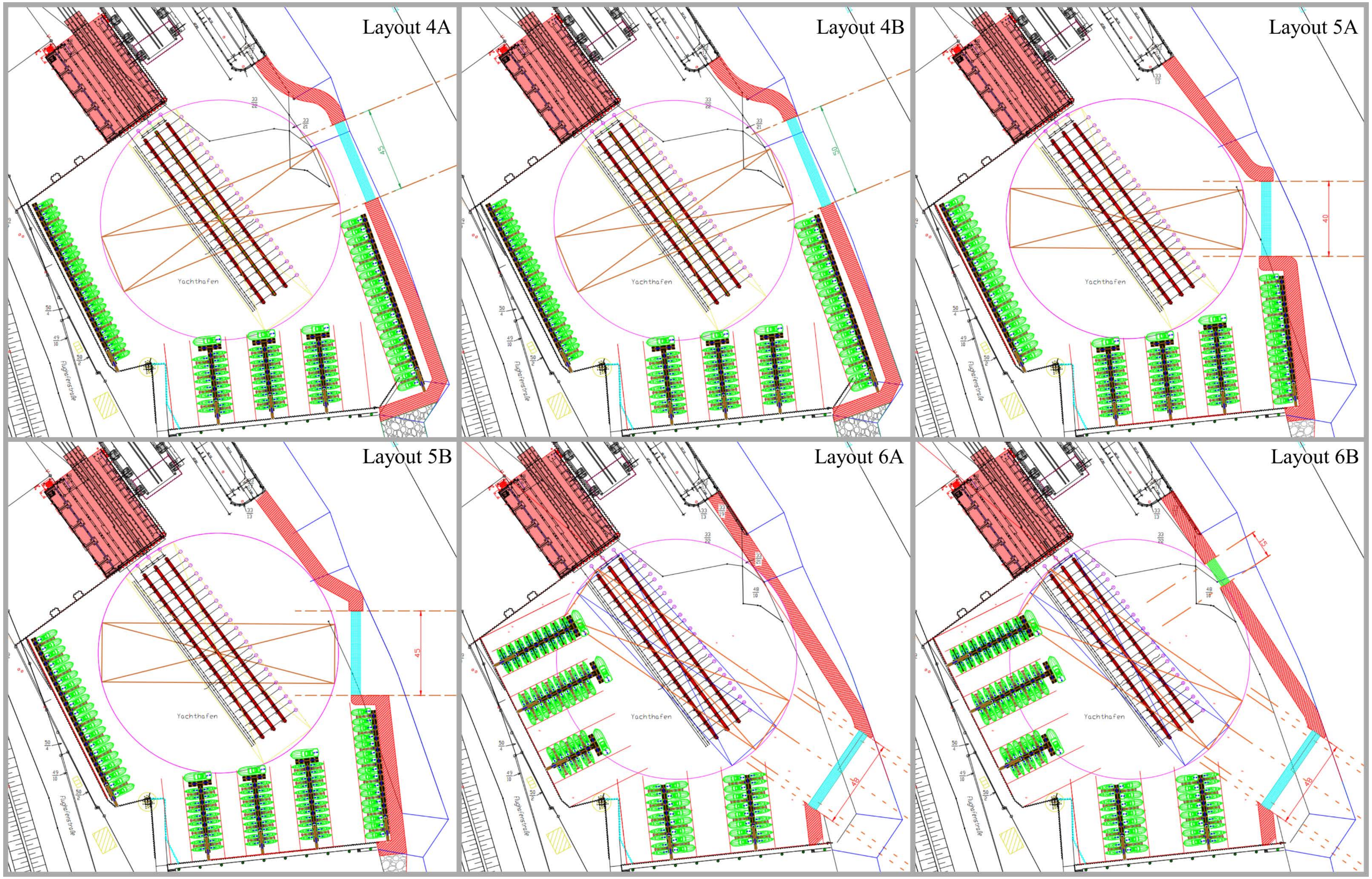


Figure 38: Brainstormed Layouts 4A-6B

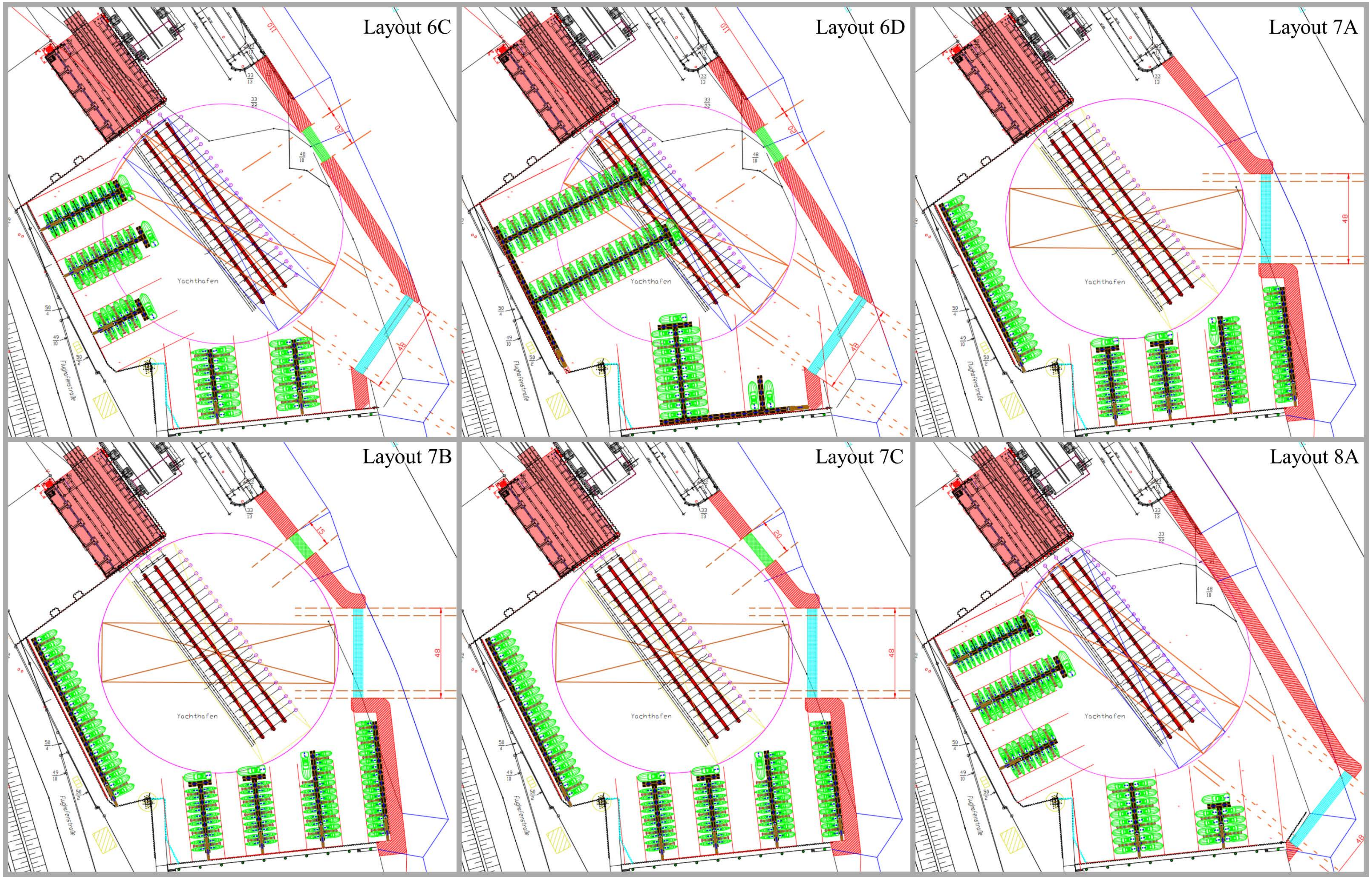


Figure 39: Brainstormed Layouts 6C-8A

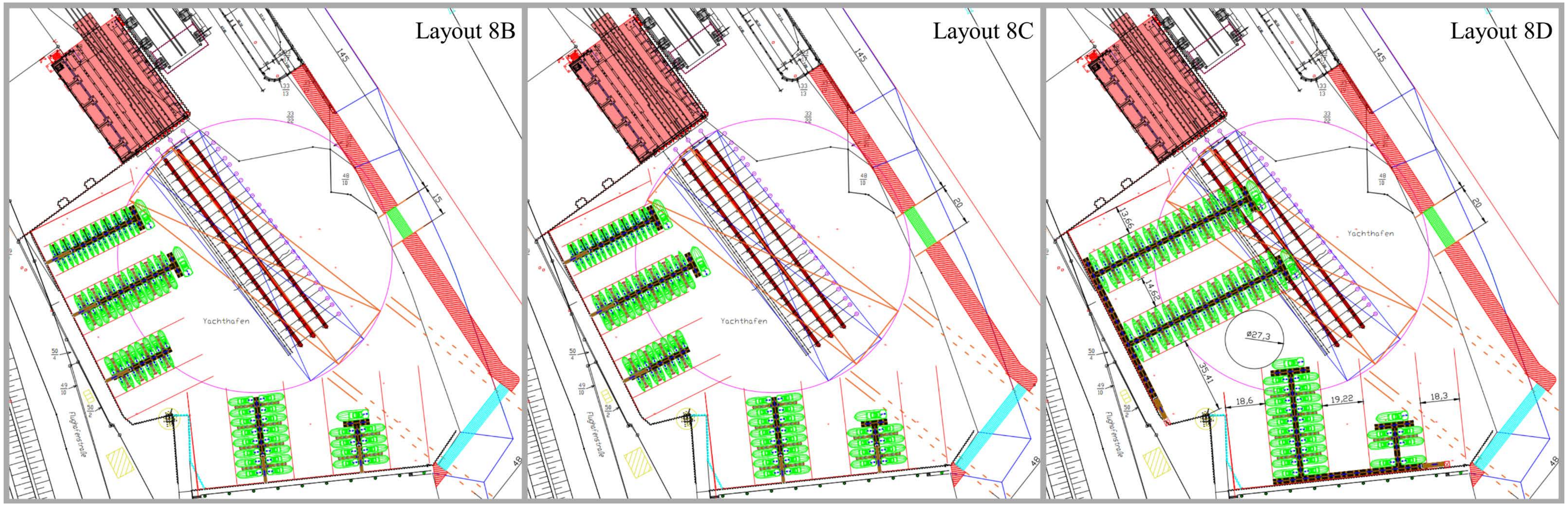
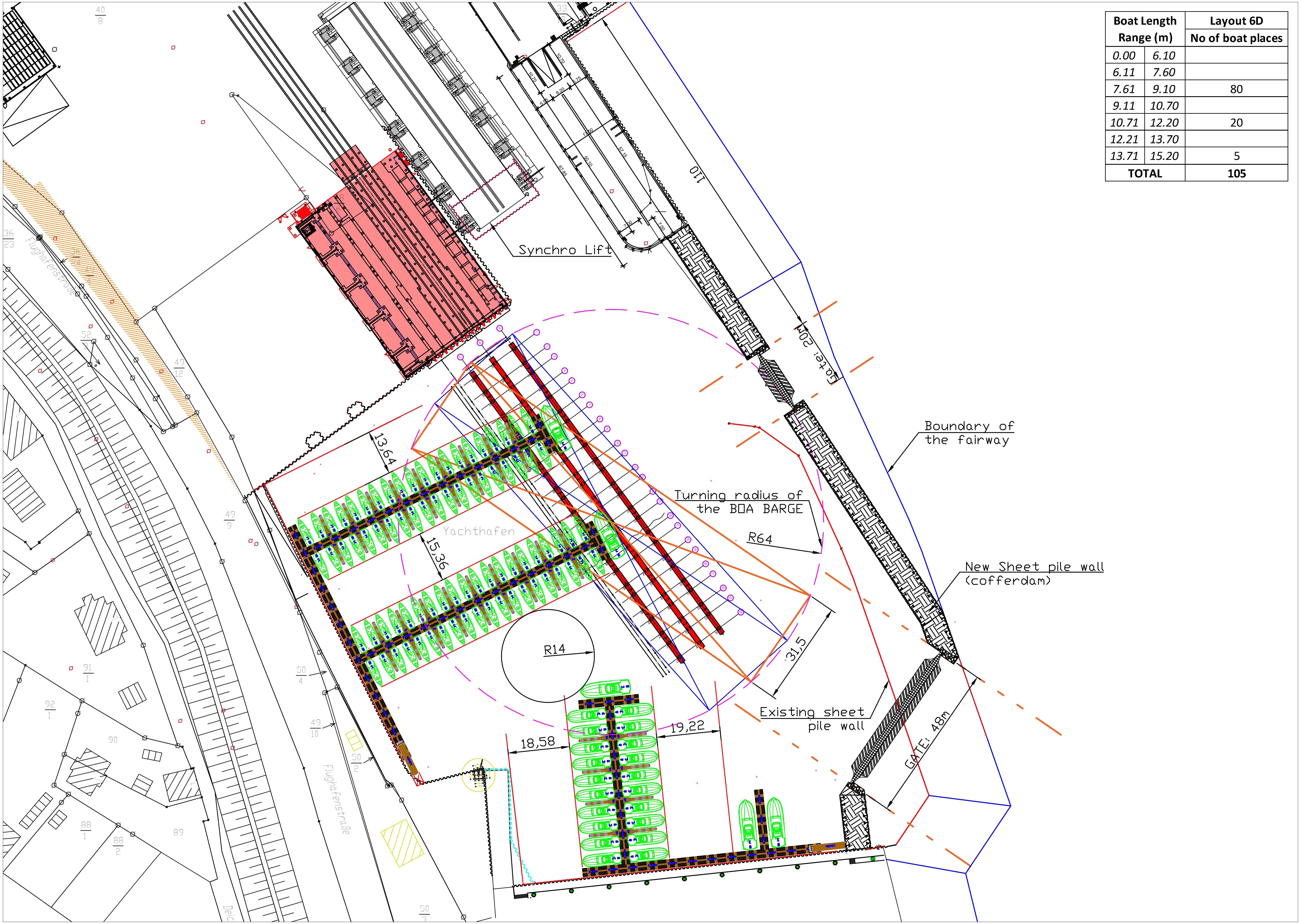


Figure 40: Brainstormed Layouts 8B-8D

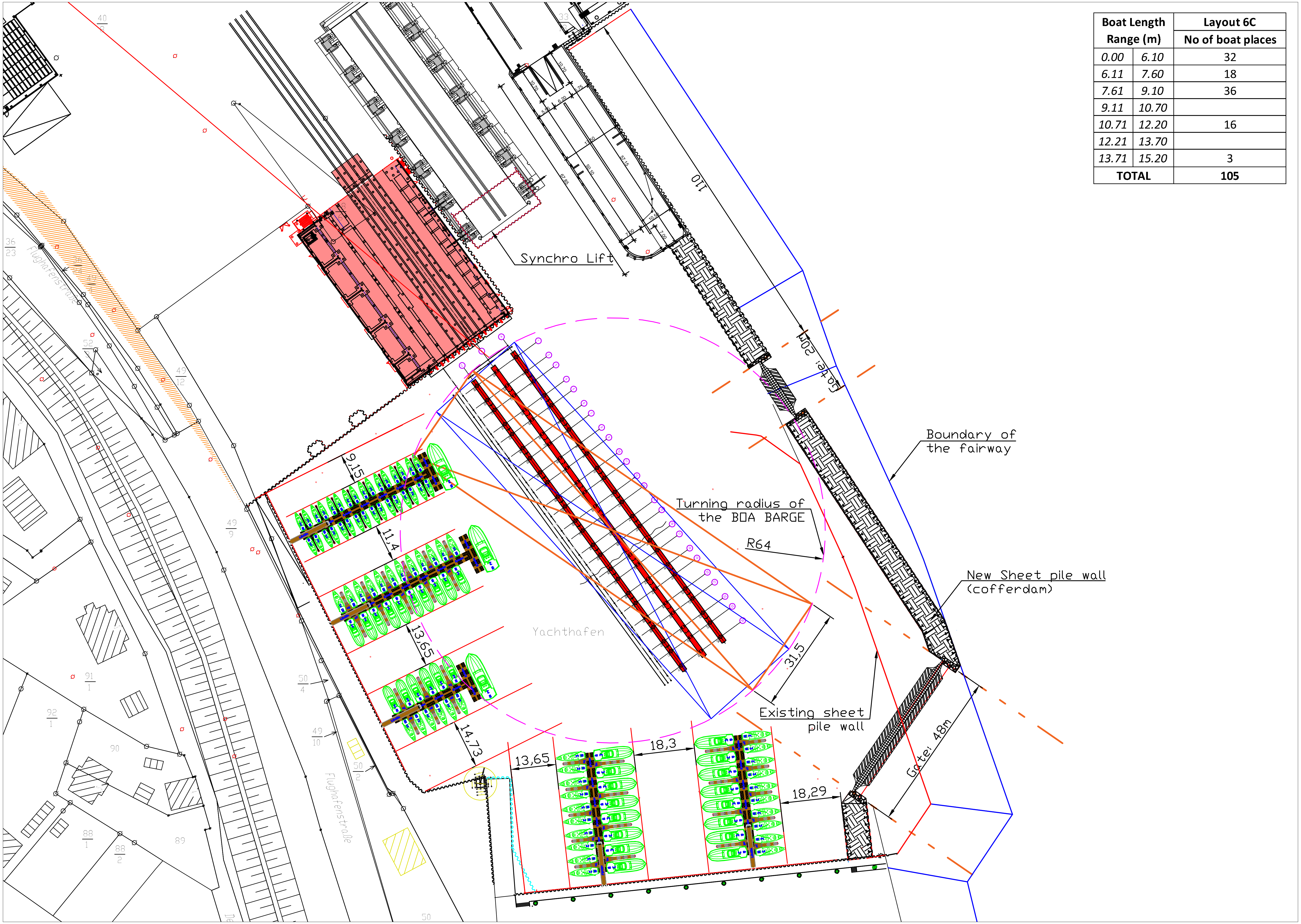
APPENDIX III

The top four scored layouts can be seen on the following pages in A3 format.

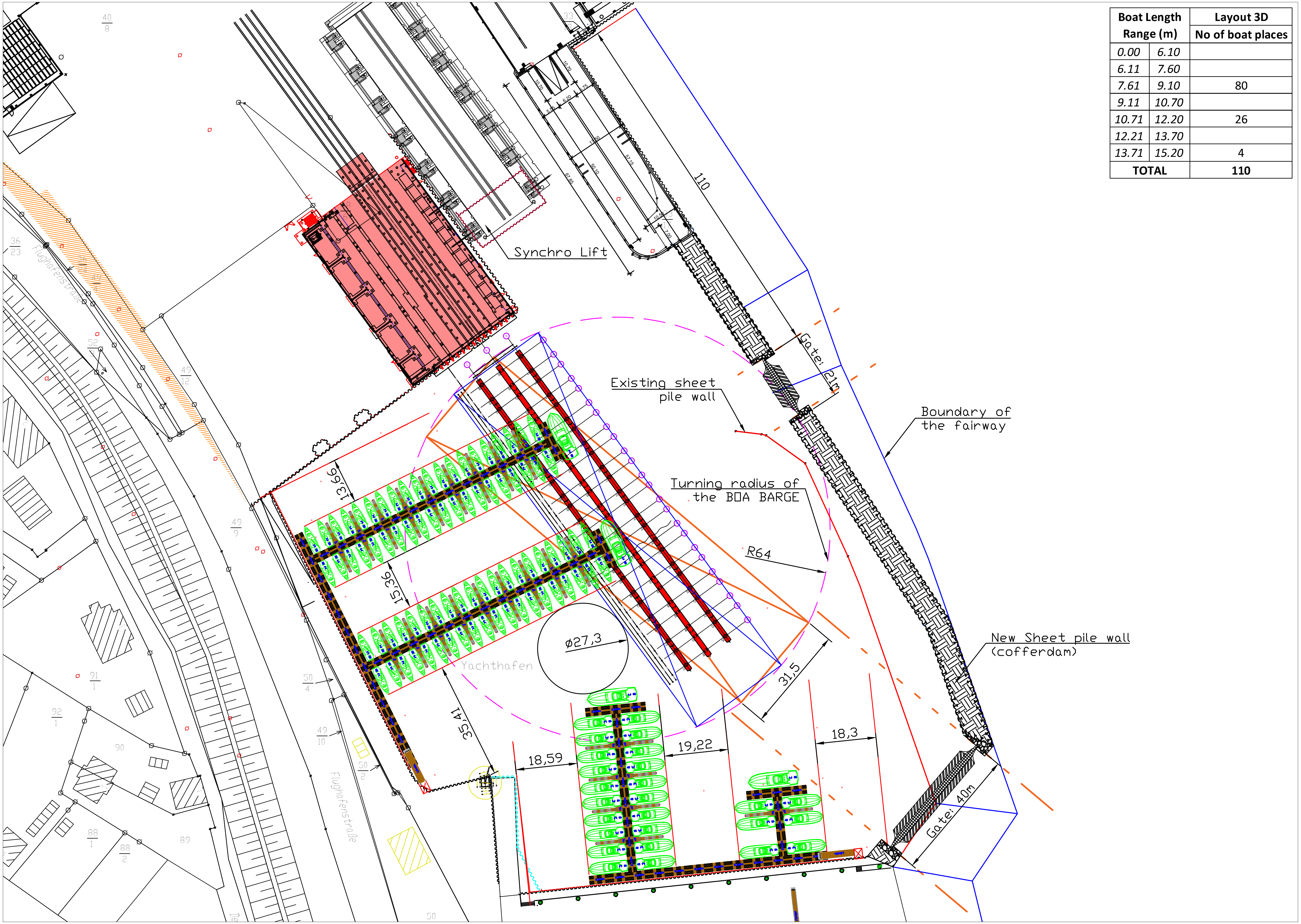
Boat Length Range (m)		Layout 6D
		No of boat places
0.00	*6.10*	
6.11	*7.60*	
7.61	*9.10*	80
9.11	*10.70*	
10.71	*12.20*	20
12.21	*13.70*	
13.71	*15.20*	5
TOTAL		**105**



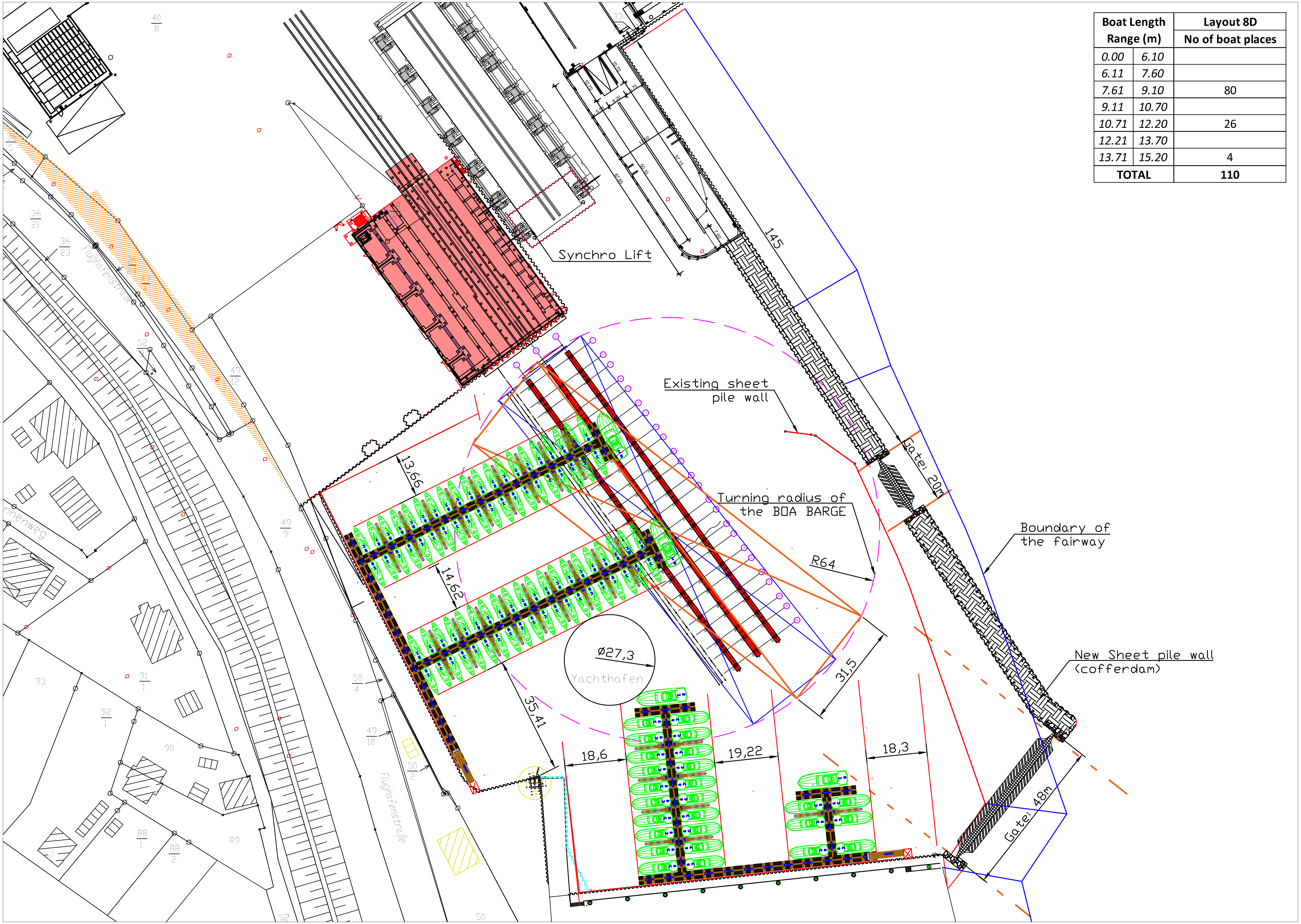
Boat Length Range (m)		Layout 6C No of boat places
0.00	6.10	32
6.11	7.60	18
7.61	9.10	36
9.11	10.70	
10.71	12.20	16
12.21	13.70	
13.71	15.20	3
TOTAL		105



Boat Length Range (m)		Layout 3D No of boat places
0.00	6.10	
6.11	7.60	
7.61	9.10	80
9.11	10.70	
10.71	12.20	26
12.21	13.70	
13.71	15.20	4
TOTAL		**110**



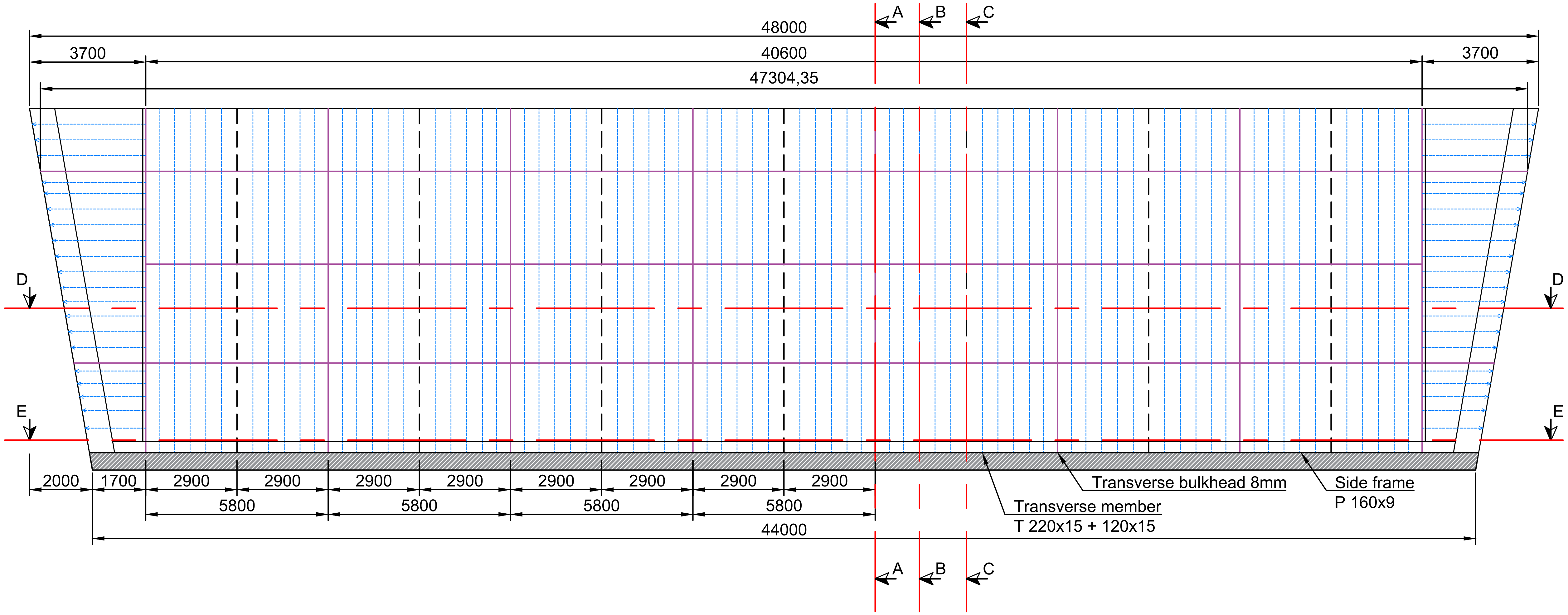
Boat Length Range (m)		Layout 8D No of boat places
0.00	*6.10*	
6.11	*7.60*	
7.61	*9.10*	80
9.11	*10.70*	
10.71	*12.20*	26
12.21	*13.70*	
13.71	*15.20*	4
TOTAL		**110**



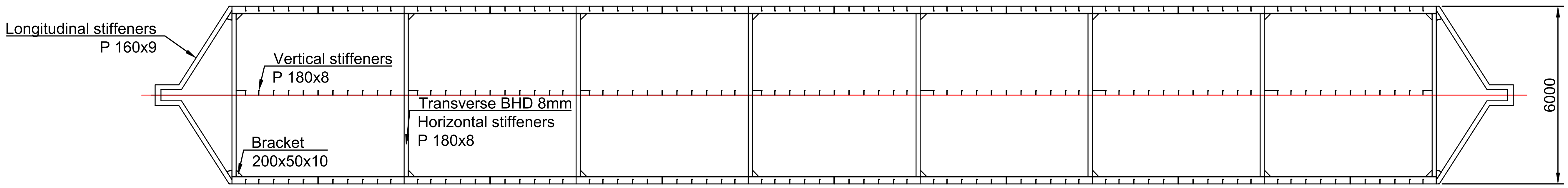
APPENDIX IV

Floating door hull scantling drawings are presented in the following two pages in A3 format.

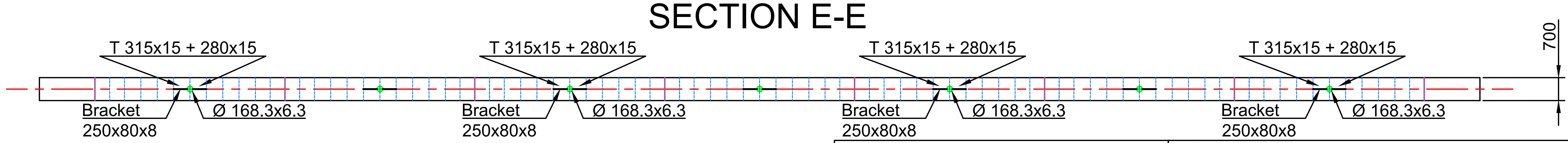
SIDE VIEW



SECTION D-D

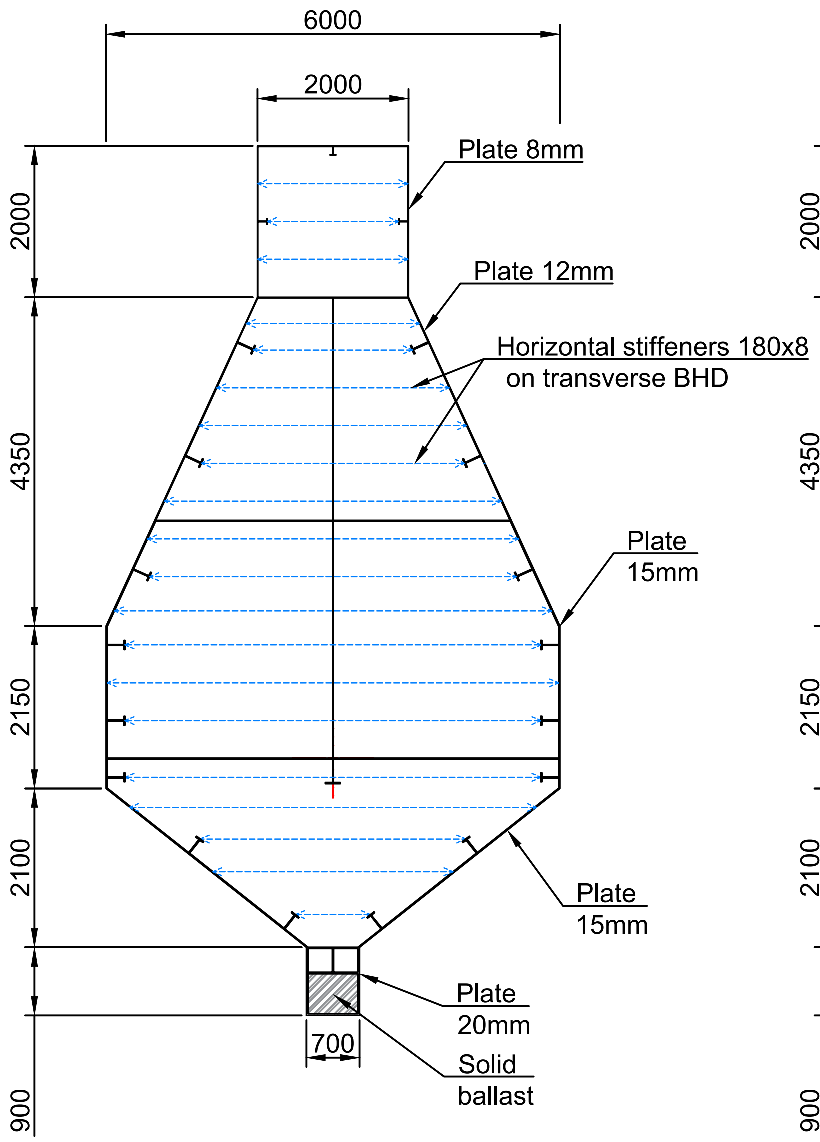


SECTION E-E

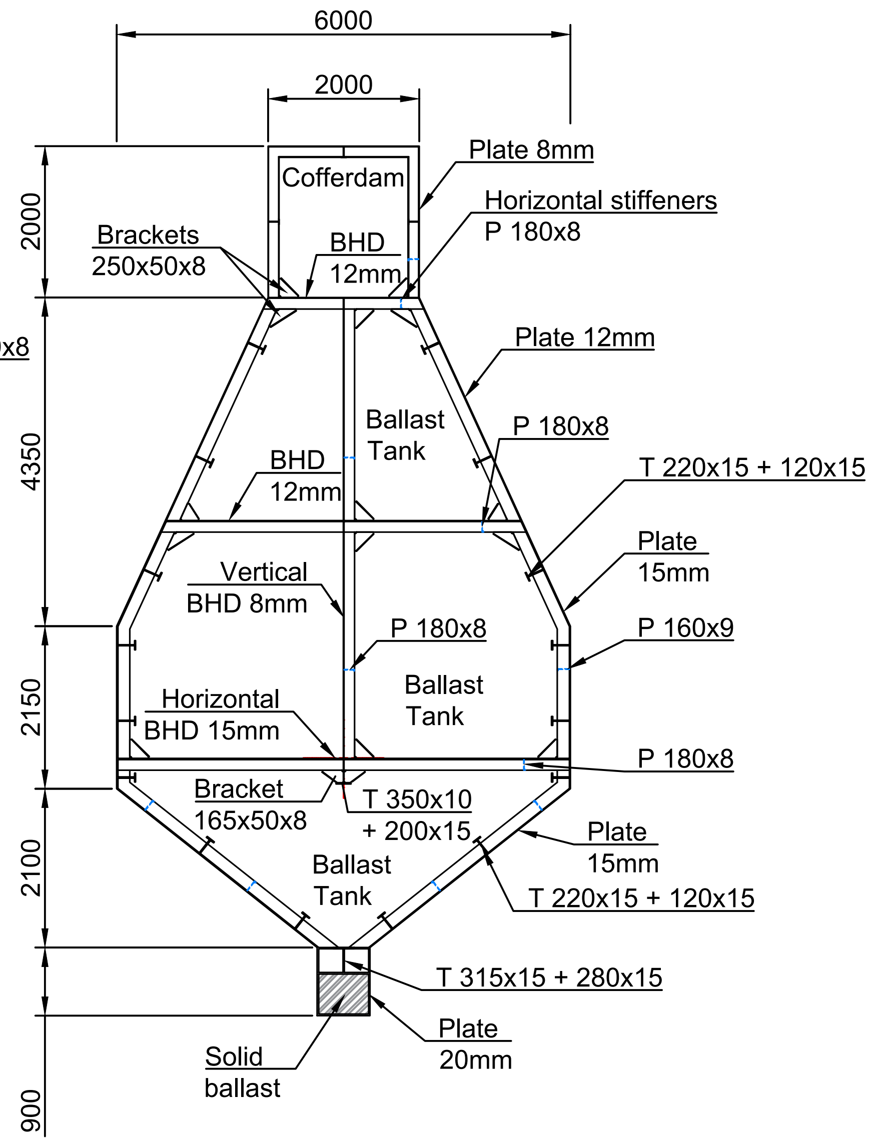


Client: Abeking & Rasmussen	Title: Floating Door				
Project: Master Thesis					
Work nr: 1	Stage: PP	Project part: FD	Drawing nr: 1	Version: 2	Scale: 1:150(A3)
Draftsman:	K. Tull				02.01.2018
Designer:	K. Tull				02.01.2018
Checker:	A. Skalicky				02.01.2018
Fail name:	Rev 1_Caisson design.dwg				

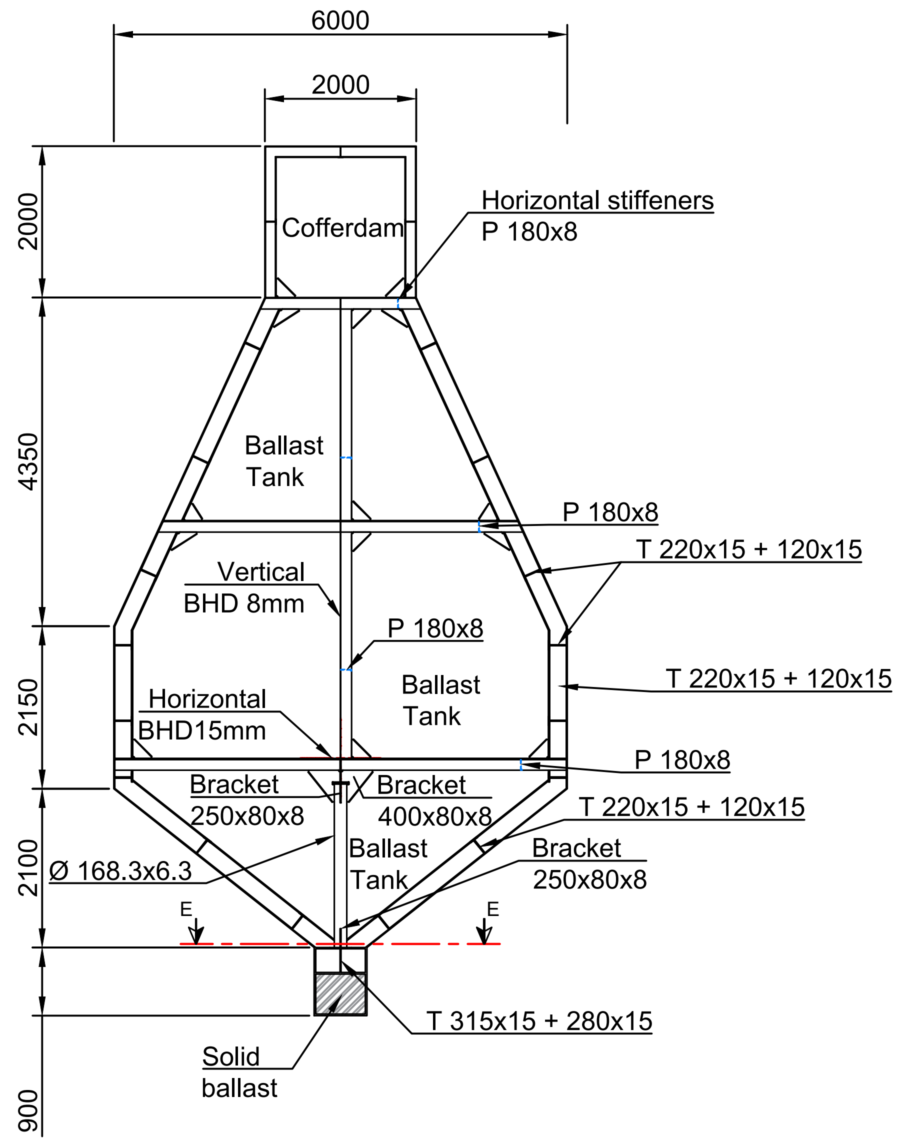
SECTION A-A



SECTION B-B



SECTION C-C



Client: Abeking & Rasmussen	Title: Floating Door					
Project: Master Thesis						
	Work nr: 1	Stage: PP	Project part: FD	Drawing nr: 2	Version: 2	Scale: 1:100(A3)
	Draftsman:	K. Tull				02.01.2018
	Designer:	K. Tull				02.01.2018
	Checker:	A. Skalicky				02.01.2018
	Fail name:	Rev 1_Caisson design.dwg				

APPENDIX V

Table 36: Floating Door Weight Estimation

Transverese section (considers side plating, horizontal bulkheads (floors) and keel plating)			
Description	**Abbrev.**	**Amount**	**Unit**
Density of steel:	ρ_{steel}	7850.000	kg/m^3
Total transverese sectional area from autocad:	$A_{T,ts}$	733005.098	mm^2
Total transverse sectional area in m2:	$A_{T,ts}$	0.733	m^2
Length between end bulkheads from autocad:	$L_{BHD,ts}$	40.600	m
Volume of trasnverese section steel:	V_{ts}	29.760	m^3
Weight in kg:	W_{ts}	233616.055	kg
Weight in ton:	W_{ts}	233.7	t

Solid keel			
Solid keel ballast sectional area from autocad:	$A_{in,3}$	349800.000	mm^2
Solid keel ballast length from autocad:	$A_{in,3}$	44.070	m
Volume of the ballast:	V_{ts}	15.416	m^3
Density of concrete:	p	2500.000	kg/m3
Weight of solid ballast keel in kg:	W	38539.215	kg
Weight of solid ballast keel in t:	W	38.6	t

Horizontal section (considers the vertical bulb profiles and T-profiles) - Frames			
Description	**Abbrev.**	**Amount**	**Unit**
Section area of one vertical bulb profile from autocad:	A_{bulb}	1619.076	mm^2
Amount of vertical bulbs in horizontal section view:	$N_{o, bulb}$	217.000	pc
Total sectional area of bulb profiles in horizontal section:	$A_{T,bulb}$	351339.427	mm^2
Section area of one vertical T- profile from autocad:	A_{T-prof}	5325.000	mm^2
Amount of vertical T-profiles in horizontal section view:	$N_{o, T-prof}$	14.000	pc
Total sectional area of T- profiles in horizontal section:	$A_{T,T-prof}$	74550.000	mm^2
Total bulb and T-profile sectional area:	$A_{T,b+t}$	425889.427	mm^2
Total bulb and T-profile sectional area in m2:	$A_{T,b+t}$	0.426	m^2
Length considered vertically (height) from autocad:	L_V	12.669	m
Volume of steel in horizontal section:	V_{hs}	5.396	m^3
Weight in kg	W_{hs}	42355.206	kg
Weight in ton	W_{hs}	42.4	t

Horizontal stiffeners on floors (180 x 8)			
Description	**Abbrev.**	**Amount**	**Unit**
Sectional area of the bulb (140x8) from autocad:	A_{bulb}	1294.187	mm^2
Amount of horizontal bulbs in horizontal section view:	$N_{o, bulb}$	77.000	pc
Total area of the bulbs:	$A_{T,ss}$	99652.399	mm^2
Total area of the bulbs in m^2:	$A_{T,ss}$	0.100	m^2
Length of the bulb profiles:	L_V	6.000	m
Volume of steel of the horizontal stiffeners on floors:	V_{hs}	0.598	m^3
Sectional area of the bulb (140x8) from autocad:	A_{bulb}	1294.187	mm^2
Amount of horizontal bulbs in horizontal section view:	$N_{o, bulb}$	77.000	pc
Total area of the bulbs:	$A_{T,ss}$	99652.399	mm^2
Total area of the bulbs in m^2:	$A_{T,ss}$	0.100	m^2
Length of the bulb profiles:	L_V	4.692	m
Volume of steel of the horizontal stiffeners on floors:	V_{hs}	0.468	m^3
Sectional area of the bulb (140x8) from autocad:	A_{bulb}	1294.187	mm^2
Amount of horizontal bulbs in horizontal section view:	$N_{o, bulb}$	77.000	pc
Total area of the bulbs:	$A_{T,ss}$	99652.399	mm^2
Total area of the bulbs in m2:	$A_{T,ss}$	0.100	m^2
Length of the bulb profiles:	L_V	2.000	m
Volume of steel of the horizontal stiffeners on floors:	V_{hs}	0.199	m^3
Total volume of steel of floor bulb profiles:	V_{ss}	1.265	m^3
Weight in kg:	W_{ss}	9928.588	kg
Weight in ton:	W_{ss}	**10.0**	**t**

Horizontal stiffeners on vertical bulkheads (160 x 8)			
Description	**Abbrev.**	**Amount**	**Unit**
Sectional area of one horizontal bulb profile stiffener on BHD:	A_{bulb}	1294.187	mm^2
Amount of vertical bulkheads:	$N_{o, BHD}$	8.000	pc
Total sectional area of bulb profiles on BHD:	$A_{T,bulb,bhd}$	10353.496	mm^2
Total sectional area of bulb profiles on BHD in m2:	$A_{T,bulb,bhd}$	0.010	m^2
Total length of bulb profile stiffeners on one BHD:	$L_{BHD,h}$	75.348	m
Volume of steel of BHD stiffeners:	$V_{h,sb}$	0.780	m^3
Weight in kg	$W_{h,sb}$	6123.924	kg
Weight in ton	$W_{h,sb}$	**6.2**	**t**

Vertical bulkheads			
Description	**Abbrev.**	**Amount**	**Unit**
Area of one vertical bulkhead in transverse section view from acad:	$A_{V,BHD}$	41580000.000	mm^2
Amount of vertical bulkheads:	$N_{o, BHD}$	8.000	pc
Total sectional area of vertical bulkheads:	$A_{T,BHD}$	332640000.000	mm^2
Total sectional area of vertical bulkheads in m2:	$A_{T,BHD}$	332.640	m^2
Thickness of vertical bulkhead:	t_{BHD}	0.008	m
Total volume of steel of bulkheads:	$V_{v,BHD}$	2.661	m^3
Weight in kg	$W_{v,BHD}$	20889.792	kg
Weight in ton	$W_{v,BHD}$	20.9	t

Aft and forward part longitudinal stiffeners (considers the triangle and nose part)			
Description	**Abbrev.**	**Amount**	**Unit**
Sectional area of one longitudinal bulb profile stiffener:	A_{hs}	1619.076	mm^2
Sectional area of one longitudinal bulb profile stiffener in m2:	$A_{T,bulb,hs}$	0.002	m^2
Amount of sides (port and starboard):	$N_{o, BHD}$	4.000	pc
Total length of bulb profile stiffeners on 4 sides (triangle+nose):	L_{hs}	349.856	m
Volume of steel of aft and forward part longitudinal stiffeners:	V_{hs}	0.566	m^3
Weight in kg	W_{hs}	4446.580	kg
Weight in ton	W_{hs}	4.5	t

Aft and forward part horizontal bulkheads (floors in the trinagle part of the structure)			
Description	**Abbrev.**	**Amount**	**Unit**
Sectional area of lower horizontal bulkhead from acad:	A_{hs}	5821937.309	mm^2
Amount of lower horizontal bulkheads:	$N_{o, BHD}$	2.000	pc
Total sectional area of lower bulkheads:	$A_{T,BHD}$	11643874.619	mm^2
Total sectional area of lower bulkheads in m2:	$A_{T,BHD}$	11.644	m^2
Thickness of aft/forward part horizontal bulkhead plating:	t_{BHD}	0.015	m
Total sectional area of upper and lower bulkheads in m2:	$V_{h,BHD}$	0.175	m^3
Sectional area of upper horizontal bulkhead from acad:	A_{hs}	4070434.783	mm^2
Amount of upper horizontal bulkheads:	$N_{o, BHD}$	2.000	pc
Total sectional area of upper bulkheads:	$A_{T,BHD}$	8140869.565	mm^2
Total sectional area of upper bulkheads in m2:	$A_{T,BHD}$	8.141	m^2
Thickness of aft/forward part horizontal bulkhead plating:	t_{BHD}	0.012	m
Volume of steel of aft/forward horizontal bulkheads:	$V_{h,BHD}$	0.098	m^3
Volume of steel of aft/forward horizontal bulkheads:	$V_{h,BHD}$	0.272	m^3
Weight in kg	$W_{h,BHD}$	2137.936	kg
Weight in ton	$W_{h,BHD}$	2.2	t

1# Aft and forward part plating of the nose			
Description	**Abbrev.**	**Amount**	**Unit**
Sectional area of aft/forward plating from acad:	A_p	45200.000	mm^2
Amount of noses (aft/forward):	$N_{o,p}$	2.000	pc
Sectional area of aft/forward plating:	A_p	90400.000	mm^2
Sectional area of aft/forward plating in m2:	A_p	0.090	m^2
Length considered vertically (height) from acad:	L_{vp}	11.673	m
Total volume of aft/forfard part nose plating	V_p	1.055	m^3
Weight in kg	$W_{p\#1}$	8283.356	kg
Weight in ton	$W_{p\#1}$	8.3	t

2# Aft and forward part plating of the sides			
Description	**Abbrev.**	**Amount**	**Unit**
Sectional area of aft/forward plating from acad:	A_p	5807263.039	mm^2
Amount of platings (4 corners):	$N_{o,p}$	4.000	pc
Total area of aft/forward plating:	A_p	23229052.155	mm^2
Total area of aft/forward plating in m2:	A_p	23.229	m^2
thickness of the superstructure plating	t	0.008	m
Total volume of aft/forfard part nose plating	V_p	0.186	m^3
Sectional area of aft/forward plating from acad:	A_p	8608501.438	mm^2
Amount of platings (4 corners):	$N_{o,p}$	4.000	pc
Total area of aft/forward plating:	A_p	34434005.750	mm^2
Total area of aft/forward plating in m2:	A_p	34.434	m^2
thickness of the superstructure plating	t	0.012	m
Total volume of aft/forfard part nose plating	V_p	0.413	m^3
Sectional area of aft/forward plating from acad:	A_p	10674275.470	mm^2
Amount of platings (4 corners):	$N_{o,p}$	4.000	pc
Total area of aft/forward plating:	A_p	42697101.879	mm^2
Total area of aft/forward plating in m2:	A_p	42.697	m^2
thickness of the superstructure plating	t	0.015	m
Total volume of aft/forfard part nose plating	V_p	0.640	m^3
Sectional area of aft/forward plating from acad:	A_p	6497462.966	mm^2
Amount of platings (4 corners):	$N_{o,p}$	4.000	pc
Total area of aft/forward plating:	A_p	25989851.866	mm^2
Total area of aft/forward plating in m2:	A_p	25.990	m^2
Thickness of the superstructure plating:	t	0.015	m
Total volume of aft/forfard nose plating	V_p	0.390	m^3
Total volume of aft/forfard side plating	V_p	1.629	m^3
Weight in kg	$W_{p\#2}$	12790.357	kg
Weight in ton	$W_{p\#2}$	12.8	t

Pillars			
Description	**Abbrev.**	**Amount**	**Unit**
Sectional area of aft/forward plating from acad:	A_p	**3206.310**	mm^2
Amount of platings (4 corners):	$N_{o,\ p}$	**7.000**	pc
Total area of aft/forward plating:	A_p	**22444.167**	mm^2
Total area of aft/forward plating in m2:	A_p	**0.022**	m^2
thickness of the superstructure plating	**H**	**2.167**	m
Total volume of aft/forfard part nose plating	V_p	**0.049**	m^3
Weight in kg	$W_{p\#2}$	**381.797**	kg
Weight in ton	$W_{p\#2}$	**0.4**	**t**
TOTAL ESTIMATED WEIGHT IN TON	W_{TOTAL}	**380.0**	**t**