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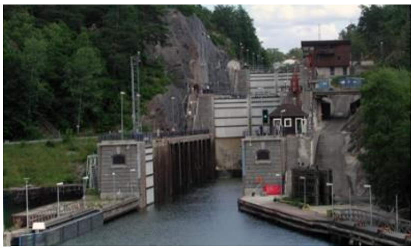
Report.

No: RE41178514-05-00-A

Report Title: Battery electric inland waterway vessel



Interreg North Sea Region #IWTS 2.0

European Regional Development Fund

EUROPEAN UNION

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REPORT

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Project Manager:

Staffan Sjöling

Author

Martin Ericson Borgh,
Daniel Kågedal,
Staffan Sjöling

+46 (31) 772 90 00

Summary

A battery electric inland waterway vessel concept has been developed. The vessel is designed to carry 160 TEUs (twenty-foot containers) between the port of Gothenburg and Trollhättan, with a frequency of five times/week. The vessel has the largest possible dimensions allowed for passage through the locks in Trollhättan, and is designed for lean manning, ice class 1C and entirely electrically propelled.

The vessel has a battery capacity of 6.1 MWh, which is capacity for one single journey between the two ports. The amount of batteries is large and will be an expensive investment.

The study shows that it is possible to transport a large number of containers on pure electric power if the distance between the ports is reasonably short.

SSPA Sweden AB	SSPA Sweden AB
Vendela Santén	Staffan Sjöling
Project Manager, Research	*Project Manager, Naval Architect*

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1 Background

1.1 Project aims

The aim of the project has been to develop a battery electric inland waterway vessel for container transport on the river Göta älv. The route between the port of Gothenburg and Trollhättan is relatively short making pure electric transport viable. The route is in protected waters with foreseeable weather conditions. The locks in Trollhättan set the maximum size of the ship. The objective has therefore been to develop a vessel with maximum cargo capacity and with a size possible to go through the locks.

The entire route is within the area for Swedish inland waterway transport. In 2014, new requirements for inland waterway vessels came into force through the Swedish Transport Agency's, STA, and regulation TSFS 2014:96. The requirements enables quite a few relaxations compared to requirements on sea going vessels. TSFS 2014:96 has been amended to the later described TSFS 2018:60.

The river Göta älv is in Inland waterways zone 3. The mouth of the river, and the port of Gothenburg, is zone 2 and Lake Vänern is zone 1. The main focus of the vessel's operations is Göta älv. Vänern is therefore not in primary interest for the operations of this particular vessel concept. However, the possibility to also traffic Vänern ports has also been accounted for in the design, as an alternative routing. Extending the vessel's area of operation to include also Lake Vänern mainly affects its ice going capabilities and its range.

In 2020, the boundaries of the area for inland waterway vessels will most likely be expanded, covering also the coastal zones, north of Gothenburg. This will make the possible use of the vessel on other extended, alternative routes, but has not been taken into account for in this design.

The vessel concept has been designed with limited resources and time, and should not be considered as a full design. A few items and arrangements need further development to fully optimize the design, especially more details related to the weight calculations. Weight calculation has a strong impact on cargo carrying capacities, vessel resistance and stability, and would benefit from further development.

1.2 IWTS 2.0

The vessel concept has been developed as part of Interreg North Sea Region IWTS 2.0 project (Inland Waterway Transport Solutions). IWTS 2.0 runs between 2017-2020 and involves partners in Netherlands, Belgium, Germany, United Kingdom and Sweden. SSPA is the only Swedish partner. The aim of the IWTS 2.0 project is to "mobilise potentials and capacity to move freight to yet-underused waterways".

The Swedish part of the IWTS 2.0 project focuses on the development of innovative logistics concepts for coastal and inland shipping that looks beyond current limitations in existing business models, legislation, goods flow characteristics and vessel concepts. Apart from Interreg North Sea Region, also VINNOVA, the Sweden's Innovation Agency, and Region Västra Götaland support the Swedish part of the research with funding. Collaboration partners in Sweden have been University of Gothenburg (School of Business, Economics and Law), Avatar Logistics and Seadvise.

Results achieved so far in the ongoing IWTS 2.0 project, have created an understanding for possible logistics concepts of inland waterway shipping in Sweden. Today there are no inland waterway vessels operating on Swedish inland waterways. Current limited traffic consists only of IMO vessels. During 2019, a Multi-Actor-Multi-Criteria-Analysis (MAMCA) was performed, assessing five actor groups' viewpoints on three different business concepts for inland shipping on Göta älv and Vänern. The actor groups were authorities, goods owners, shipping companies, ports and freight forwarders. The business concept found to be most preferable was an emission free shuttle, electrified, operating between the coastal port (Gothenburg) and a nearby (<100 km) inland port. The idea with the emission free shuttle was to use the available inland waterways as an emission-free option for transporting containers between inland goods owners and the coastal port, where the close distance makes it possible with a high frequency (5 roundtrips/week). Today there is no transshipment of containers between ships and inland vessels at Port of Gothenburg, only between ship and road/rail. Using the inland waterways to a larger extent would reduce the need for heavy land traffic in the urban, as well as the port area, and thereby also reduce emissions from trucks. The emission free shuttle concept includes an inland port area (e.g. in Trollhättan), where additional logistics services, such as stuffing and stripping of containers, as well as a container depot would create positive benefits for customers. The battery electric inland waterway vessel described in this report, should be possible to apply in a logistics setting like the emission free shuttle.

2 Conditions for inland waterway vessel development

2.1 Vessel targets

The vessel has been developed with a few main targets. These targets all support the main target of a transport solution for an efficient and environmentally sustainable alternative to present transport on roads and on railway.

The main targets for the project are:

- The vessel shall be designed for container transport on Göta älv
- The vessel should be able to carry at least 150 TEUs (Twenty-foot containers)
- The vessel should be able to carry other cargoes
- The vessel shall be able to make five return trips Gothenburg-Trollhättan per week
- The vessel should have a turn-around time Gothenburg-Trollhättan-Gothenburg of 24 hours
- The vessel shall be powered, to the furthest extent, by battery electricity
- The vessel shall have a minimum speed of 10 knots
- The vessel should be able to traffic Lake Vänern
- The vessel shall be designed for lowest possible environmental footprint
- The vessel shall be designed and fitted for low life cycle cost
- The vessel shall be designed for year-round traffic

- The vessel shall be designed for lean manning
- The vessel shall fulfil statutory requirements
- The vessel may use shore-based cargo handling equipment

The one most outstanding target is to power the vessel with battery electric propulsion. Batteries require large spaces and the vessels range is directly dependent on the amount of batteries. In the Swedish context, similar transport solutions do not exist today. The cargo ships that operate on Göta älv-river are all diesel powered and classified according to IMO regulations.

2.2 Göta älv

The river Göta älv reaches from Lake Vänern to Kattegat just outside Gothenburg, see Figure 1. The start of the river is at Vargön, just north of Trollhättan. The river is 50 nm long and the width varies between 50 to 400 m. The mean water flow is about 550 m^3/h, which results in a current of about maximum 1.5-2 kn.

Figure 1 Göta älv river, Port of Gothenburg (in blue), Lilla Edet (in red) and Trollhättan (in black) (source: www.sjofartsverket.se)

The lowest depth in the entire route is 5.85 m at Marieholmsbron. The river is rarely covered in ice, but during cold winters there can be large amounts of ice sheets from areas upriver. Speed limitations in the river is from five to 10 knots. The route from port of Gothenburg to Trollhättan is 45 nm long. A number of bridges cross the river. The lower bridges all open for passing ships. In table 1, limiting heights below bridges on Göta älv are described.

Table 1 Height under bridges

Göta älv/The Trollhätte Canal	Max air draught, [m]
Älvsborg bridge	H = 45,0
Göta älv bridge	H = 18,3
Marieholm bridge	H = 5,9
Angered bridge	H = 47,0
Jordfall bridge	H = 11,0
Lilla Edet bridge	H = 10,0
Klaffbron, Trollhättan	H = 3,5
Railway bridge, Trollhättan	H = 2,8
Stall bridge (not openable)	H = 28,0
Grop bridge, Vänersborg	H = 4,0
Railway bridge, Vänersborg	H = 2,0
Dalbo bridge, Vänersborg	H = 15,5 – 17,0

2.3 Port of Gothenburg

Port of Gothenburg is the largest port in Sweden. About 30 % of the international trade and about 60 % of the Swedish container trade passes the port yearly. The port handles 753 000 TEUs yearly. Containers are handled in the Skandia-port, with an area of about 80 hectare and about 1 750 m quays only for container vessels, see Figure 2 for sea chart visualisation. The port can handle vessels up to 400 m with a draught up to 13.5 m. The port is equipped with seven large container-cranes where the two largest are of 23-container wide reach super post-panama STS-type.

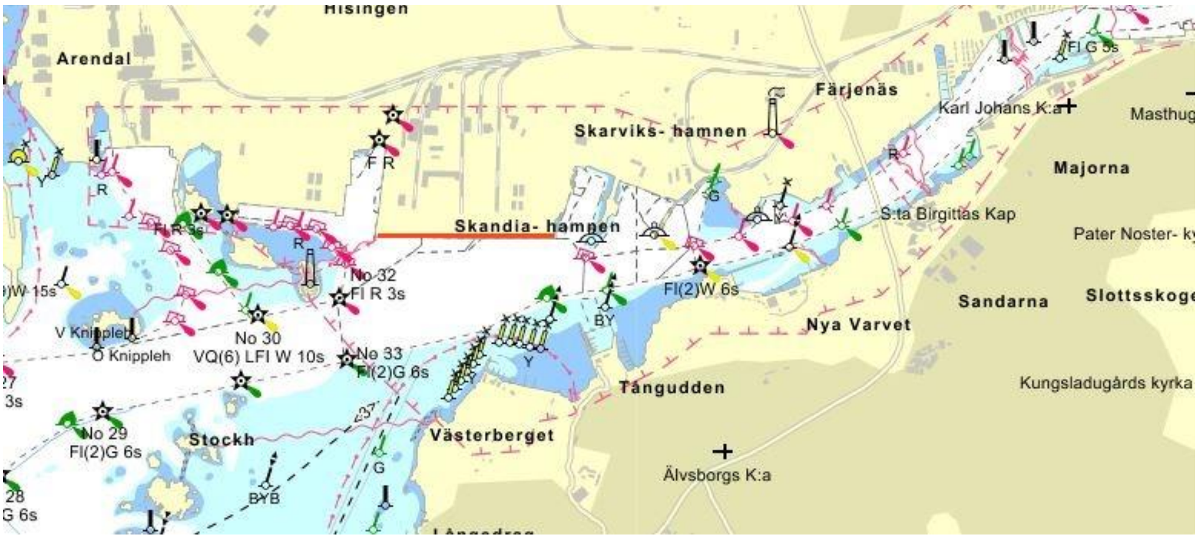


Figure 2 Sea chart Port of Gothenburg (source: www.eniro.se)

2.4 Trollhättan port

The northern port of one possible route on Göta älv is Trollhättan. There is a terminal right by the fairway at Stallbacken, see Figure 3. The terminal is not fully developed for container transport today but has potential to be an efficient container terminal in the future. The location is close to the railway and the regional motorways Road 44 and Road E45.

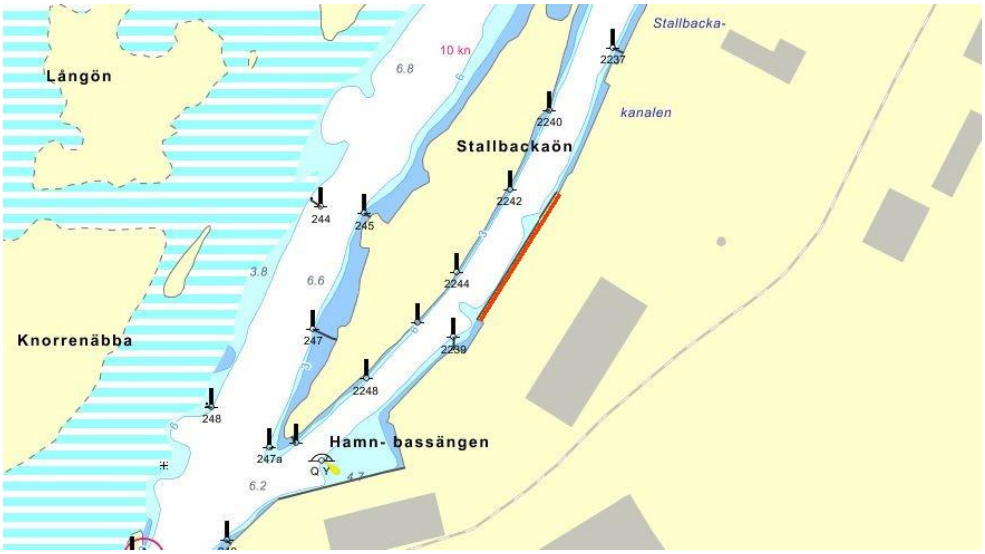


Figure 3 Sea chart Trollhättan port (source: www.eniro.se)

The port does not have handling equipment for container cargo. In order to make one return trip within 24 hours a capacity of at least 45 containers per hour must be provided, further explained in chapter 3 below. This capacity could be provided with equipment, such as a hydraulic material handling crane, a gantry crane or a large reach stacker, see examples in Figure 4.

Figure 4 Reach stacker and a hydraulic material handling crane (source: kalmarglobal.com and mantsinen.com)

2.5 Trollhättan locks

Göta älv has six locks, one in Lilla Edet, four just south of Trollhättan and one between Trollhättan and Vänersborg. The total height difference is 44 m, 39 m between the sea and Trollhättan port.

At the Trollhättan locks, see Figure 5, there are mooring hooks that can be released from the lock central. The lock crew will also provide support with mooring during locking. Loaded ships with length larger than 83 m shall be moored at four ends during lock-operations. The lowest depth in the Trollhättan locks is 5.65 m, 5.5 m during low water.

The largest size of vessel allowed to pass through the Trollhättan locks is L 87 m, B 12.7 m, T 4.7 m. Larger ships are allowed after given special permit from the Swedish Maritime Administration. The largest size with special permit is L 89 m, B 13.4 m, T 5.4 m.

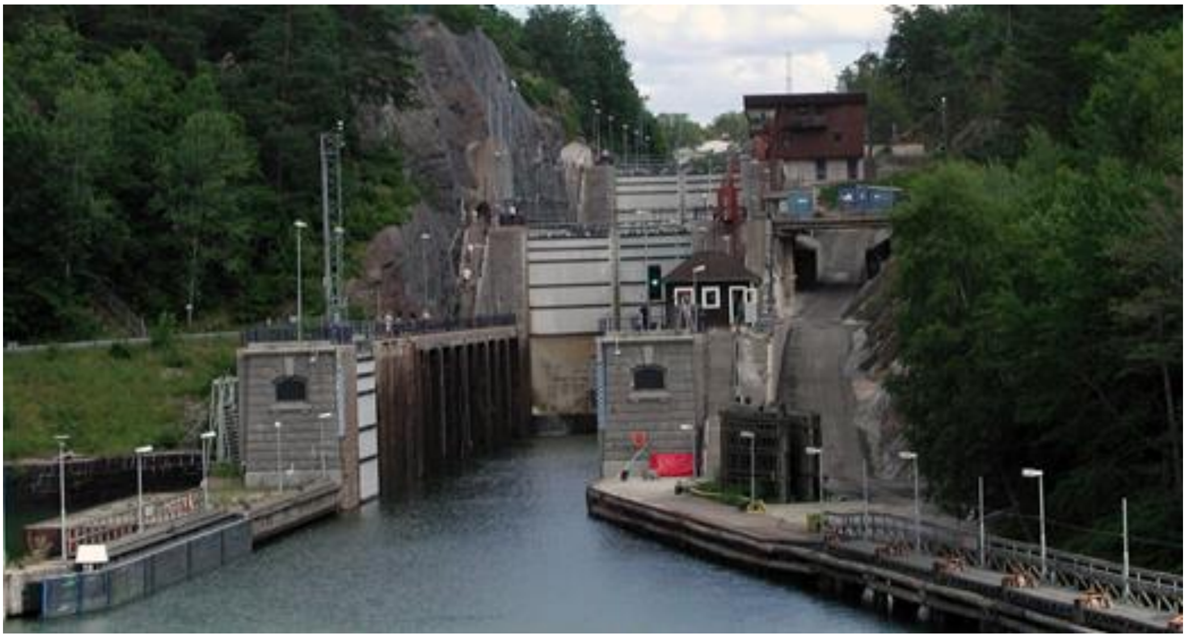


Figure 5 Locks of Trollhättan from south (source: www.sjofartsverket.se)

2.6 Lake Vänern

Göta älv runs from Lake Vänern to Gothenburg. Lake Vänern is Sweden's largest lake and is 5 650 km^2 large. During winter the lake is normally covered in ice, although variations between years exist. Medium ice thickness over the last twenty years is 0.35 m. The largest ports in Lake Vänern are Gruvön, Lidköping, Karlstad, Kristinehamn and Otterbäcken. See Figure 6, for AIS-track densities in Vänern.

The purpose of the inland waterway vessel concept is not to call the ports around Lake Vänern. The possibility of calling these ports should however not be excluded.

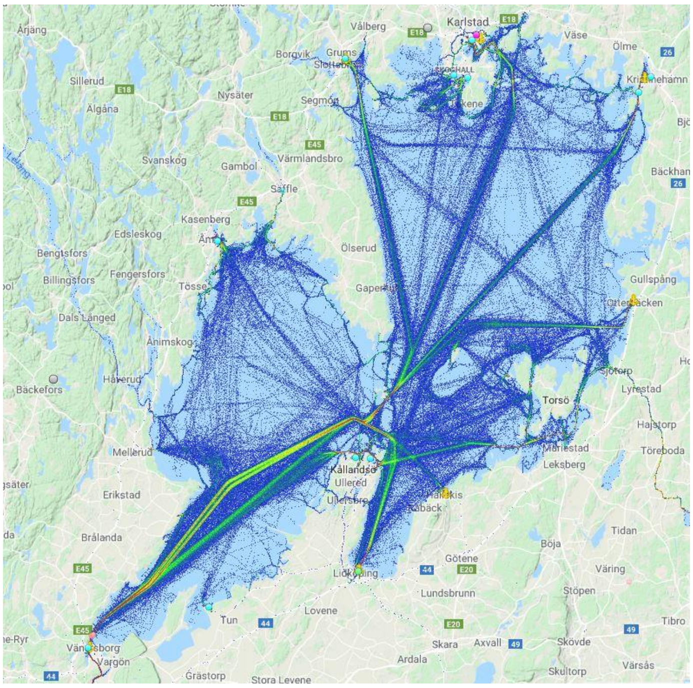


Figure 6 Lake Vänern, with AIS-track densities (source: www.marinetraffic.com)

2.7 Regulations

The ship is assumed to be designed for national traffic under Swedish flag. In order to operate on Göta älv and Vänern the statutory requirements are set by TSFS 2018:60, *Transportstyrelsens föreskrifter och allmänna råd om fartyg i inlandssjöfart (Swedish Transport Agency's requirements on shipping on inland waterways),* further pointing at the applicable technical requirements of ES-TRIN-standard, ES-TRIN, European Standard, Technical requirements or Inland Navigation vessels 2015/1. The Swedish maritime administration also has special regulations for ships sailing Göta älv.

The vessel design shall meet the following technical requirements:

- The design shall meet the technical requirements of TSFS 2018:60
- The design shall meet the technical requirements of ES-TRIN 2015/1
- The design shall meet the technical requirements of the Swedish Maritime Agency's, *SMA, Special rules for transiting the Trollhätte canal with maximum-size vessels*

Further, in order to be entitled to icebreaking assistance the ship must meet technical requirements of Swedish authorities.

TSFS 2009:111, STA: s rules on Finnish and Swedish icebreaking class or SJÖFS 2013:16, Regulations and general advice of the Swedish maritime administration on Swedish ice class for traffic on Lake Vänern.

Some of the additions to ES-TRIN set by the Swedish regulations in TSFS 2018:60 are:

-Vessels operating in zone 1 or zone 2 shall have a class certificate

-Vessels operating in zone 1 shall have a margin to flooding of at least 1200 mm

-Vessels operating in zone 1 shall have a freeboard of at least 500 mm, 300 mm for zone 2

-Vessels designed for zone 2 are allowed to traffic zone 1 if the wave height is determined to be below 1.2 m during the passage

3 Operating time table

A one-way trip takes seven and a half hours on average, following the speed limits from five to 10 knots in different parts of the river. This will vary with the waiting time at locks and bridges. The passage time used in calculations is set to eight hours to have some margin.

The distance, speed and time for the different parts of the journey have been quantified, see Table 2 below, and used when developing the design concept.

Table 2 Route details

From	To	Speed Limit [knots]	Distance [nm]	Time per part [hours]	Total time after finished part [hours]	Tot distance [nm]
Container port Gothenburg	Göta älv bridge Stenpiren	8,0	4,1	0,51	0,00	0,0
Göta älv bridge, Stenpiren	Jordfall bridge Kungälv	5,0	9,6	1,92	0,51	4,10
Jordfall bridge Kungälv	Södra tjuvholmen Älvängen	10,0	6,1	0,61	2,43	13,70
Södra tjuvholmen Älvängen	Kattleberg Älvängen	5,0	2,4	0,48	3,04	19,80
Kattleberg Älvängen	Göta krökarna	10,0	7,6	0,76	3,52	22,20
Göta krokarna	South Fuxernebryggan	7,0	2,0	0,29	4,28	29,80
South Fuxernebryggan	Entry locks Lilla Edet	10,0	0,3	0,03	4,57	31,80
Entry locks Lilla Edet	Exit locks lilla Edet	-	0,5	0,50	4,60	32,10
Exit locks lilla Edet	Entry locks Trollhättan	10,0	9,7	0,97	5,10	32,56
Entry locks Trollhättan	Exit locks Trollhättan (Klaffbron)	-	2,2	1,50	6,07	42,26
Exit locks Trollhättan (Klaffbron)	To quay Trollhättan	5,0	0,6	0,11	7,57	44,46
					7,68	45,01

The time passing through the locks in Lilla Edet and Trollhättan has been determined after an analysis of AIS-data for all vessels passing the locks over one full year (2018). The lines set for entry and exit of the locks are shown in the two following pictures, see Figure 7.

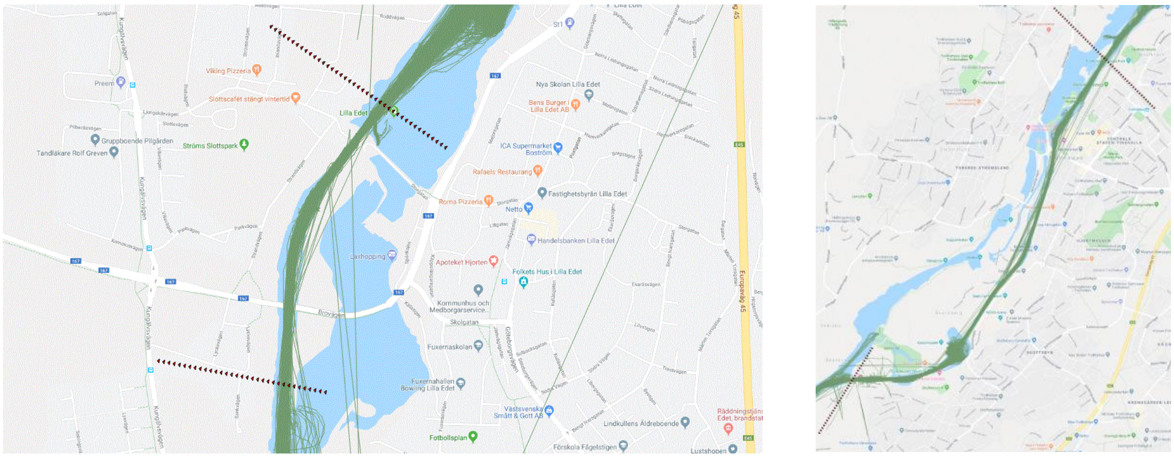


Figure 7 Lines defining entry and exit through locks in Lilla Edet and Trollhättan.

Figure 8 and 9 show examples of the results from the analysis of passages through the locks at Trollhättan (all data from lock passages are shown in appendix 2).

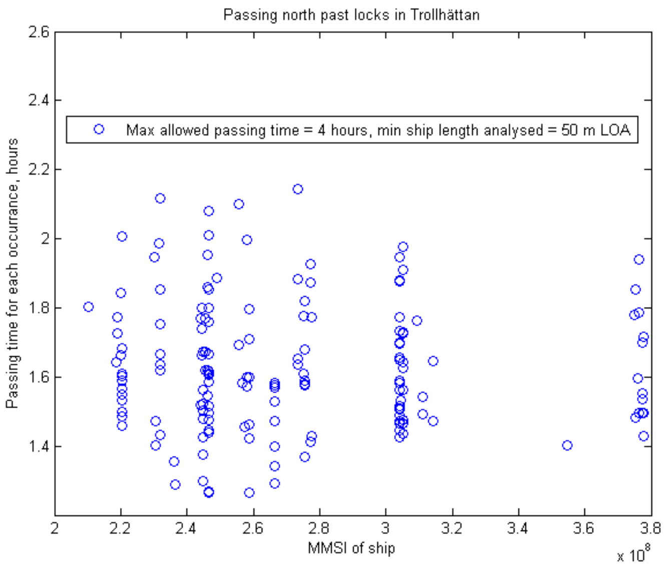


Figure 8 Data of all passages through Trollhättan locks going north (ships with LOA above 50 m)

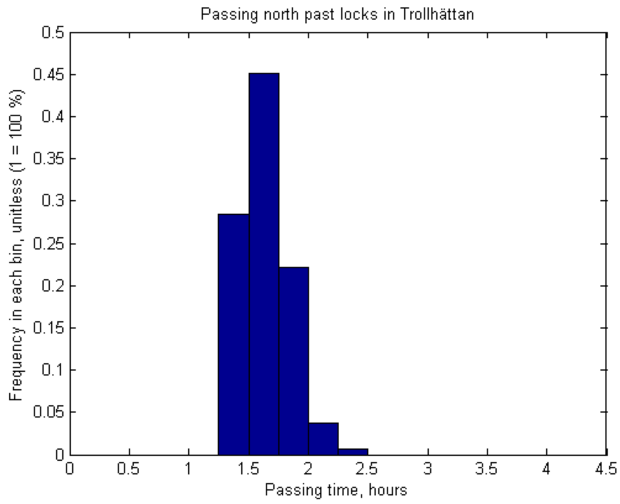


Figure 9 Frequency function of passages through Trollhättan locks going north, 15 minute time resolution (bins).

In order to allow for a return trip time of 24 hours a complete loading and unloading cycle in each port cannot take longer than 4 hours. If this is not achievable the total time for the return trip will be more than 24 hours.

With a full load of 160 TEU's at least 80 containers must be moved on/off the vessel per hour (160*2/4) to allow for a 24-hour return trip time. If the vessel is loaded with the maximum number of FEU's (70 FEUs and 20 TEU's) the loading/unloading must take place at a speed of 45 container movements per hour (90*2/4).

A loading and unloading capacity of 80 containers per hour is quite a demanding requirement, especially for the small port in Trollhättan. The target of being capable of doing a return trip in 24 hours will be difficult to meet. The number of containers that has to be moved on/off the vessel in order to make five trips per week is less, 37 containers per hour.

4 Vessel concept

4.1 Vessel arrangement

4.1.1 Forward part of ship

The vessel is a Vänern-max sized vessel with the bridge at the front of the ship. One goal with the design of the inland waterway vessel was to keep a low height, making passing under as many bridges as possible without need of opening the bridges. With the navigating bridge in the aft, it has to be high, or raised, to attain adequate visibility forward when the ship is fully laden. With the bridge on the fore, the visibility is better when passing through river bends. Aligning the vessel parallel with the locks might be more difficult with a forward bridge. Visibility from the bridge is 25 m forward of the bow (requirement 250 m in fully laden condition) and 245 deg. around the horizon (requirement 240 deg.).

Figure 10 Cargo vessel leaving the Trollhättan locks with limited visibility from bridge (source: www.svt.se)

The size of the navigating bridge is roughly 10 by 4.5 m and contains apart from the manoeuvring, navigation and engine control stations also a coffee station/kitchenette with room to seat four people, a toilet with access from both inside the bridge and from outside the deck. The bridge house may include a shower if this is desired/required for personal cleaning after deck or cargo operations – this shower shall be reachable from the deck.

The forward mast holding the forward top light, the radar, radio antenna and a signal flag mast is also placed here. The mast could be of either a telescopic or a folding type (folding forward). It is intended that the mast will be electrically powered and remotely operated from the bridge. The raised forward mast extends 12.2 m above the main deck of the vessel, or 15 m above the waterline in the lightest loaded operational mode (draught of 3.8 m).

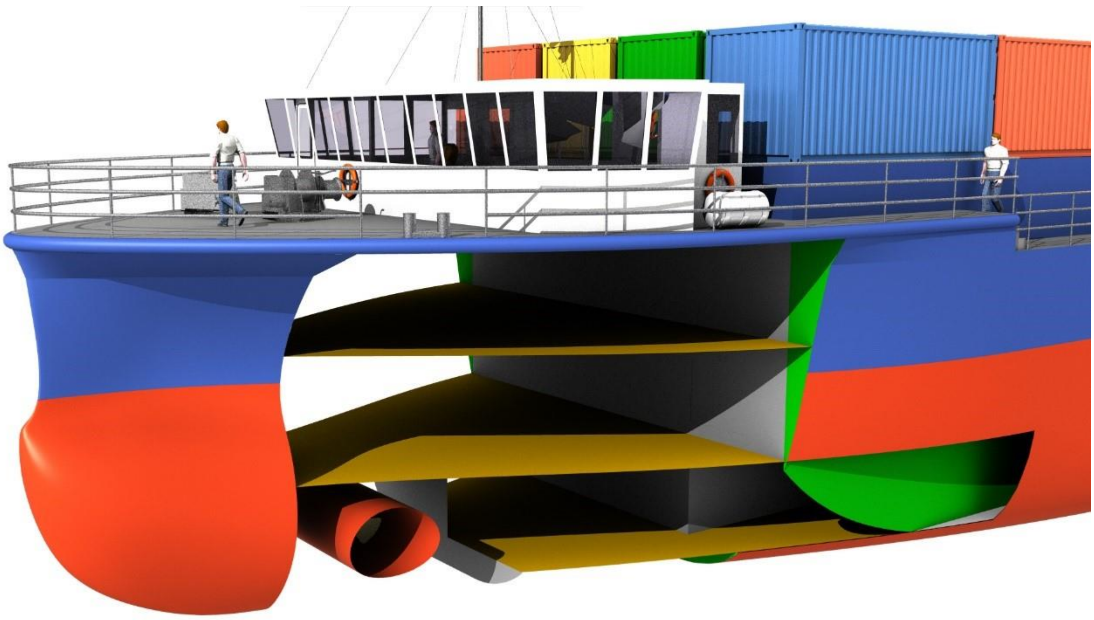


Figure 11 View of decks in fore. Green marks divisions against ballast water tanks.

The forward part of the ship also holds the crew compartment, one deck below the bridge. The deck area at this level is roughly 65 m^2 and holds the crew cabins, showers, living room with TV etc.

One deck below the crew compartment the main switchboard is situated, possibly also with the chain locker for the bow anchor. This deck may contain machinery and equipment for the bridge: heating and cooling systems, pumps etc. The deck area at this level is roughly 59 m^2.

Tanks for fresh, black and grey water together with the necessary pumps for their respective systems are placed on the deck above the double bottom. This is also a suitable place for ballast water pumps, bilge pumps and bilge water separators. A small tank for oily sludge from the bilge separator could be placed here. The total deck area at this level is roughly 56 m^2. The space aft of the forward collision bulkhead holds the bow thruster.

4.1.2 Aft part of ship

The aft part of the ship holds two battery rooms, two engine rooms, steering gear room, bunkering stations (for shore power and fuel for the generator set), mustering station and mooring equipment as well as the generator set, see Figure 12. The aft mast is placed here, holding the aft top light, NUC and other navigation lights. The mast is to be telescopic and when retracted have its highest point well below the cargo hold coamings. The mast will be powered and remotely operated from the bridge. The raised aft mast extends 17.6 m above the main deck of the vessel, or 19.4 m above the waterline in the lightest loaded operational mode (draught 3.8 m).

Figure 12 Machinery spaces in the aft part of the ship

4.1.3 Cargo hold

The cargo hold is open and not planned to be fitted with cargo hatches. Cargo hatches could be added since the cargo hold is surrounded by a coaming. The cargo holds dimensions are L 68 m B 10.85 m and D 7.1 m. The volume of the cargo hold, up to the cargo hold coaming is 4 884 m^3. For a full view of the cargo hold, see Figure 13.

The main hold has a capacity of 34 TEUs in the first layer, 40 TEUs in the second layer, 42 TEUs in the third layer and 44 TEUs in the top fourth layer. This adds up to 160 TEUs, see Figure 14 for view of the container stack.

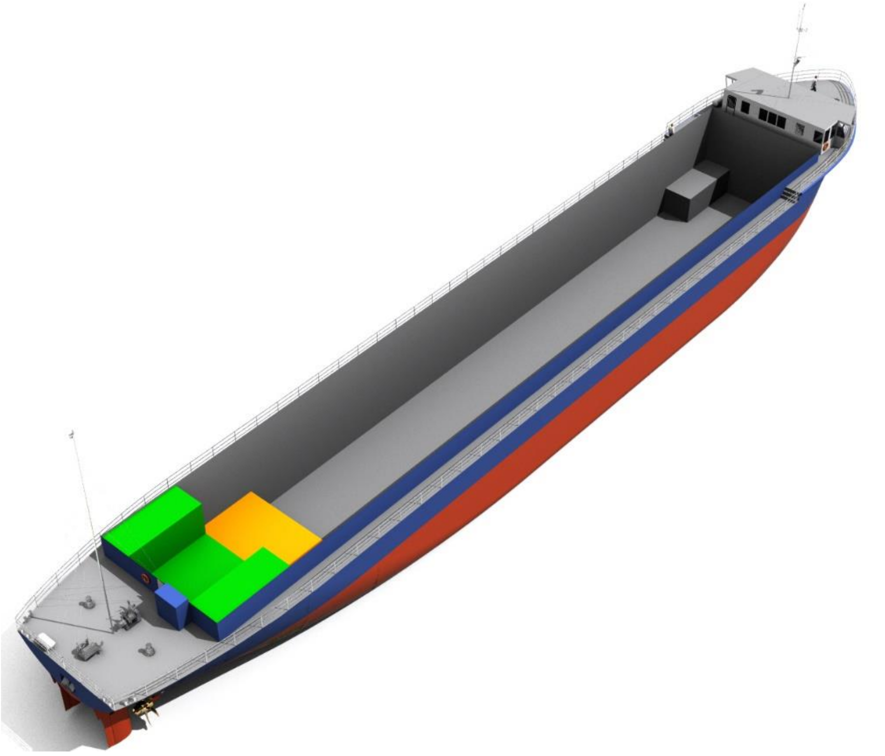


Figure 13 View of the cargo hold - the battery rooms in green and the engine rooms in yellow

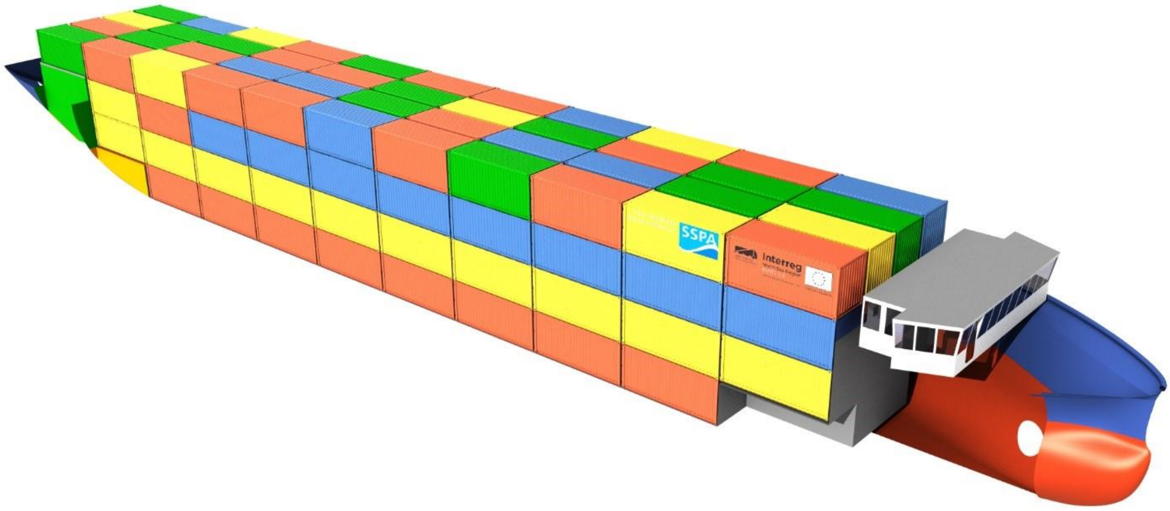


Figure 14 View of the container stack in the hull

4.1.4 Container cargo arrangements

The vessel will not be fitted with fixed cargo handling equipment of any type. All lifting operation is to be performed by handling equipment on the quay. If the vessel is to be used for container transport only and no cargo in bulk, such as grain, the hold could be fitted with fixed or semi fixed container cell guides in order to make them self-lashing and make cargo management faster, less strenuous for the crew and in all likelihood also cheaper. It has not been studied in detail, but container lashing could be made with straps and/or container locks.

4.2 Crew compartments

The crew compartment will hold three small cabins, a changing room with showers, a small kitchen and day room with seating for four people. Access to the area will be made via staircase to the bridge and, if possible, a separate stair to the deck. If a separate exit to deck via staircase is not possible, emergency exit will be through a deck hatch.

4.3 Deck arrangement

The fore deck is reached through a door on the front of the bridge, see Figure 15. Passage on the sides of the bridge house will probably be too narrow for practical daily use since the bridge must have windows to the vessel side in order to allow a clear view aft past the cargo when four container stacks are loaded. Equipment on the fore deck is an anchor winch and a mooring winch with two to four drums holding mooring lines. There is no need for a deflection roller since the winch is mounted with the axis of rotation longitudinally and the bollards can be used for deflection. The winch is to have constant tension function to allow for easier operation when passing the locks.

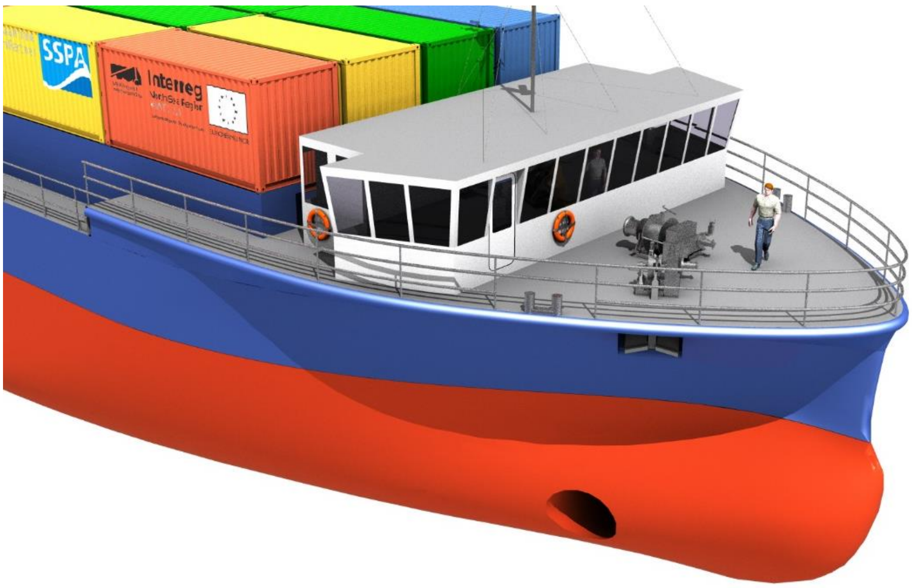


Figure 15 Fore deck with mooring and anchor arrangement

The aft deck is reached from the front of the vessel on both sides via the open deck, see Figure 16. Equipment on the aft deck is a stern anchor with winch, ES-TRIN requirement, and a mooring winch with two to four drums holding mooring lines. Two deflection rollers are included to allow for deflection to the rear of the vessel. The aft winch is also to have constant tension function. The anchor is set in the stern of the vessel with the chain locker aft of the collision bulkhead. There is also a life raft placed here launching over the stern of the vessel.

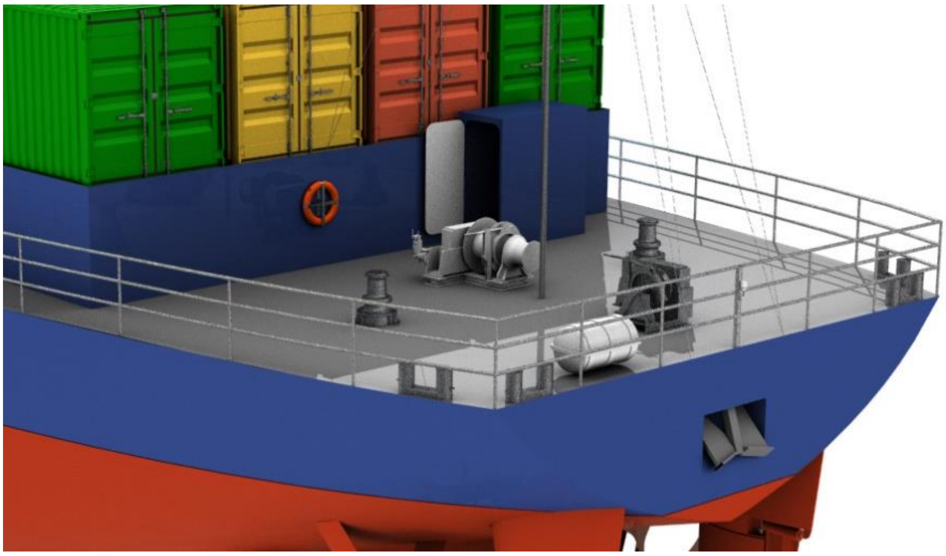


Figure 16 View over aft deck with mooring arrangement and equipment.

4.4 Subdivision

The space required to hold the 160 containers is located aft on the ship, with the navigation bridge and accommodations forward. The aft part of the cargo hold is stepped to make room for engine room and batteries.

The space between the hull and the cargo hold is used for ballast tanks. The double bottom is also used for ballast tanks, in pairs of three. Total available ballast volume is 1 340 m^3.

The subdivision of the hull can be seen in Figure 17 below and the ballast tanks in Figure 18.

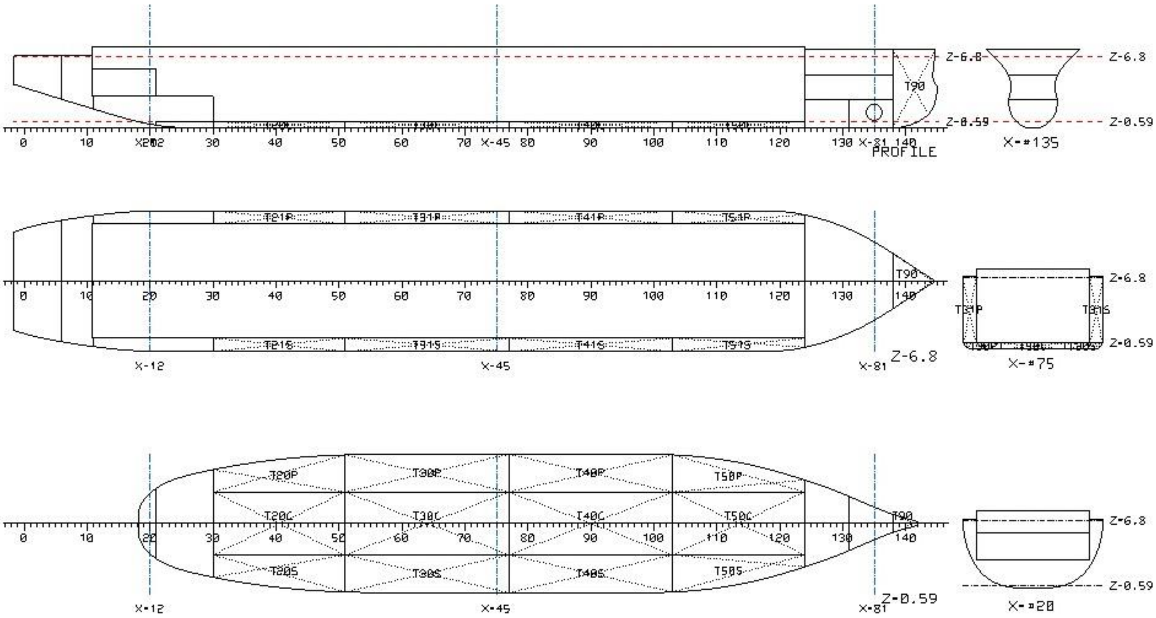


Figure 17 Subdivision of the hull

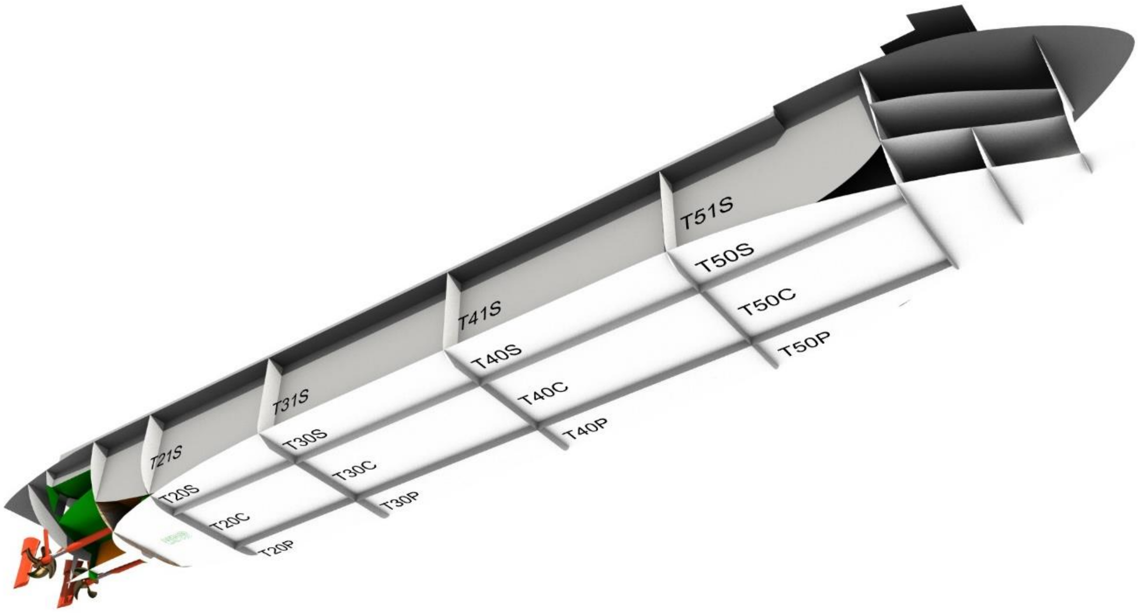


Figure 18 Subdivision of ballast tanks

4.5 Cargo Capacities

4.5.1 Container capacity

The cargo hold has been maximized to fit as many containers as possible within the restriction of the maximum size of the vessel. With the space required for accommodation, batteries, engine arrangement and auxiliary machinery arrangements 160 TEUs can be fitted in the cargo hold.

The capacity of forty-foot containers (FEU) is 70. With 70 FEUs the vessel can be filled up with 20 additional TEUs in leftover spaces.

Loading 160 TEUs will result in a vertical centre of gravity that is too high to comply with stability requirements. Ballasting is necessary. The largest amount of TEUs the vessel is able to carry without using ballast is 134.

The loading condition with 160 TEUs requires the largest amount of ballast, 1100 tons. With two ballast water pumps with the capacity of 70 m^3/h each ballasting is possible during an eight hour stay in port for loading.

The main purpose of the vessel is for transport of containers. There are a few different container sizes, from 10- to 53-foot. Container with extra height, high cube containers, are also common. The standard container size used for this inland water vessel is a TEU, length 6.058 m, breadth 2.438 and height 2.591 m. The load in each container is calculated as 12 tons. With a tare weight of 2.2 tons, each TEU thus weighs 14.2 tons. When calculating the vessels stability the vertical centre of gravity is of importance. When loading a container ship the vertical centre of gravity can be altered by stowing the heavier containers low in the cargo hold. In the case for the inland waterway vessel, the centre of gravity has been calculated as 45 % of each containers height, according to DNV-GL Pt.5, Ch.2, Sec.8.

Containers will be loaded without hatches covering the cargo hold. Covering the containers with tarps will prevent water build up during foul weather. The Swedish regulations for inland waterway transport, TSFS 2018:60, does not allow unprotected cargo holds in traffic on the deepest load line in zone 1. A solution for this has to be developed if the vessel will operate on Lake Vänern (zone 1).

4.5.2 Grain capacity

The concept vessel developed for the purpose of shipping container cargo. Inland waterway vessels of this type are usually utilized for other cargo, typically grain cargo. The concept vessel could also be used for grain shipping. With additional movable bulkheads and cargo hatches the vessel would be able to carry 4 345 m^3 grain, 3 475 tons at grain density 0.8 T/m^3. 3 475 tons is the maximum amount of grain possible to load for the vessel to have a draught less than the maximum allowed 5.4 m at the locks of Trollhättan. The cargo hold is larger. The maximum amount of grain, 3 475 tons, fills the cargo hold to 90 %. If the cargo hold is limited aft at #30, where the aft step in the cargo hold is located, the forward part of the cargo hold will be filled entirely, limiting the possibility of heeling moment due to grain shift.

Grain load results in a lower centre of gravity for the cargo, 4.15 m above keel compared to 5.95 m for 160 TEUs. Transport of grain can be made without use of ballast. Grain cargo would require cargo hold hatches and one or two transverse grain bulkheads. These have not been included in the concept.

Note: The largest draughts allowed in the ports of Gruvön, Karlstad, Kristinehamn and Lidköping is 5.3 m.

4.5.3 Timber capacity

Transport of timber is also an alternative use of the vessel. The capacity of the cargo hold is 4 884 m^3. With a load factor of 1.55 (volume of cargo hold necessary to fit 1 m^3 timber) and a timber density of 0.65 t/m^3 (birch) the amount of timber that can be carried is 2 058 tons.

If the vessel is used for transport of grain or timber it would need the support from external loading equipment. It is not planned for placing own cranes or cargo handling equipment on the vessel.

4.6 Stability

No detailed weight calculations have been made for the concept vessel. A lightweight, with centre of gravity have been derived through parametric studies of similar vessels. The derived lightweight has been corrected for the absence of a diesel engine and addition of batteries.

Seven loading conditions have been checked for floating position and stability requirement fulfilment, see example in Figure 19. These are:

- L0 Lightship
- L1 Containers 134 TEU, No Ballast
- L1B Containers 134 TEU, Ballast
- L2B Containers 150 TEU + Ballast
- L3B Containers 170 TEU + Ballast
- L4 Grain, 3475 T
- L5 Timber, 2048 T
- L6B No cargo, ballasted

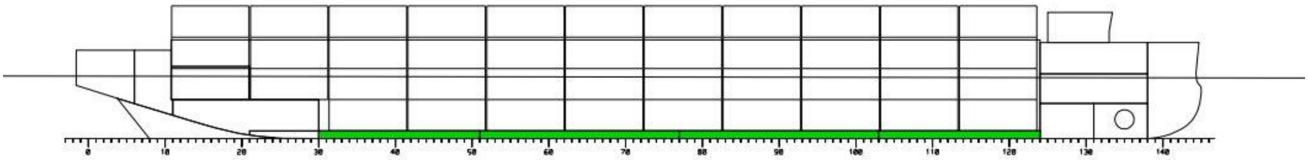


Figure 19 Floating position of loading condition L3b with 160 TEUs

Loading conditions L1 is calculated as the amount of containers that can be carried without use of ballast. With more containers the vertical centre of gravity has to be lowered with ballast to comply with stability requirements. Loading condition 2 is calculated due to the goal to carry 150 TEUs. Loading condition L6 shows ballasted condition, with no cargo and with enough ballast to immerse the propellers. The propeller tip is immersed 0.25 m below water level and will risk being ventilated.

4.6.1 Loading conditions

In Table 3 and 4 is a summary of the loading conditions for the inland waterway vessel. Loading conditions L1, L3B and L4 are shown in more detail in appendix 1.

Table 3 Loading conditions (displacement and load)

Loading conditions	Displacement	Load (DW + Ball.)
	(ton)	(ton)
L0 Lightship	1 520	0
L1 Containers 134 TEU, No Ball.	3 423	1 903
L1B Containers 134 TEU, Ball.	3 737	2 217
L2B Containers 150 TEU + Ball	4 041	2 521
L3B Containers 160 TEU + Ball	4 440	2 920
L4 Grain, 3475 T	4 995	3 475
L5 Timber, 2048 T	3 568	2 048
L6B No cargo, ballasted	2 578	1 058

Table 4 Loading conditions (draught, trim, XCG, ZCG, GM)

Loading condition	Draught	Trim	XCG	ZCG	GM
	(m)	(m)	(m)	(m)	(m)
L0	1.83	-0.49	43.50	5.52	3.37
L1	3.81	0.13	44.06	5.41	0.51
L1B	4.14	-0.01	43.76	4.98	0.84
L2B	4.43	0.18	43.73	5.22	0.51
L3B	4.81	-0.15	43.06	5.11	0.59
L4	5.35	0.04	43.01	4.57	1.12
L5	3.95	-0.27	43.37	4.83	1.05
L6B	2.96	-0.68	43.17	4.21	2.29

4.6.2 Intact stability

Stability requirements for inland waterway vessels are set in ES-TRIN. The requirements are:

- The metacentric height, MG shall not be less than 0.5 m
- Under the influence of heeling moments from turning, side wind and effect of free surfaces, no hull opening shall be immersed.

The requirement of 0.5 m MG is governing on the way the vessel is loaded. Ballast has to be used in order to meet this requirement. The different loading conditions are ballasted in a way to minimize trim.

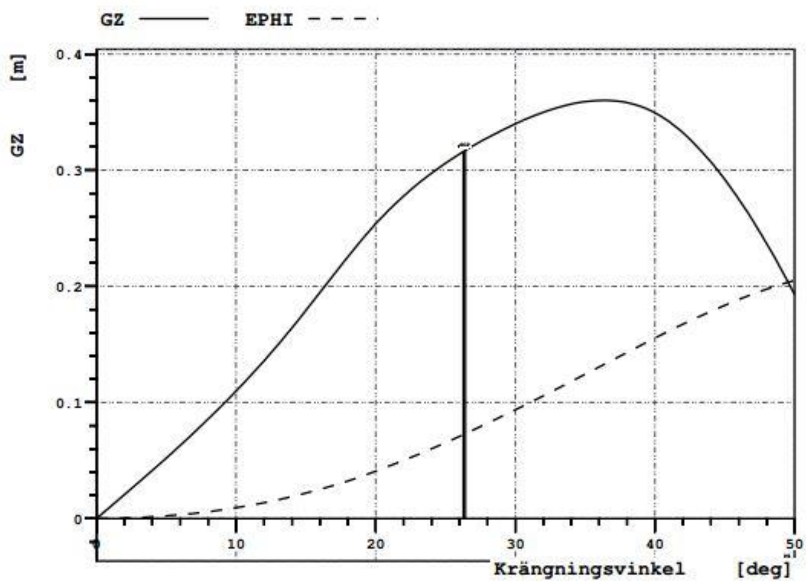


Figure 20 GZ-curve for loading condition L3B with 160 TEUs

The Swedish Transport Agency sets additional requirements for vessels on inland waterways. These are stated in TSFS 2018:60 Transportstyrelsens föreskrifter och allmänna råd om fartyg i inlandssjöfart.

Additional requirements on stability and floatability is that a minimum freeboard of 500 mm and a minimum distance from water level to nearest flooding point has to be greater than 1200 mm. Both these additional requirements are met for the calculated loading conditions. The lowest freeboard is 1550 mm for loading condition L4, with 3474 tons of grain. The lowest flooding point is 2350 above water level for the same loading condition.

Stability requirements for inland waterways are different to the standard IMO intact stability requirements. An example of this is that the metacentric height, GM, has to be larger than 0.15 m according to IMO and 0.5 m for inland waterways. For comparison, the intact stability requirements according to IMO are also given in the detailed stability results in appendix 1. Requirements are not met. This is due to flooding of the cargo hold, making fulfilment of stability requirements of area under GZ-curve difficult to be met. If cargo hold hatches would be used also the IMO intact stability requirements would be fulfilled.

4.6.3 Damage stability

Apart from requirements on an aft and forward collision bulkhead, there are no requirements on stability in damaged condition for inland waterway vessels (ES-TRIN).

The vessel has been fitted with a double bottom with 600 mm height and side tanks for ballast. Ballasting is needed both for lowering the centre of gravity and for trimming for optimal floating position when loading different cargoes. The double bottom and side tanks are also necessary for structural stability.

With the double bottom and sides, the vessel achieves good floatability if damaged. The floating after damage with a longitudinal extent that is between ballast tank bulkheads only increases draught and trim in acceptable extent. Heel and remaining righting lever, GZ, are also acceptable after damage. The vessels survivability after damage is dependent on an intact cargo hold. If the cargo hold is flooded the vessel will sink.

Figure 21-23 show the results from a few of the calculated damage conditions. Grain loading condition L4 results in most severe damages, since ballast tanks are not filled before damage.

Figure 21 shows damaged floating position for loading condition L4 with extensive aft damage.

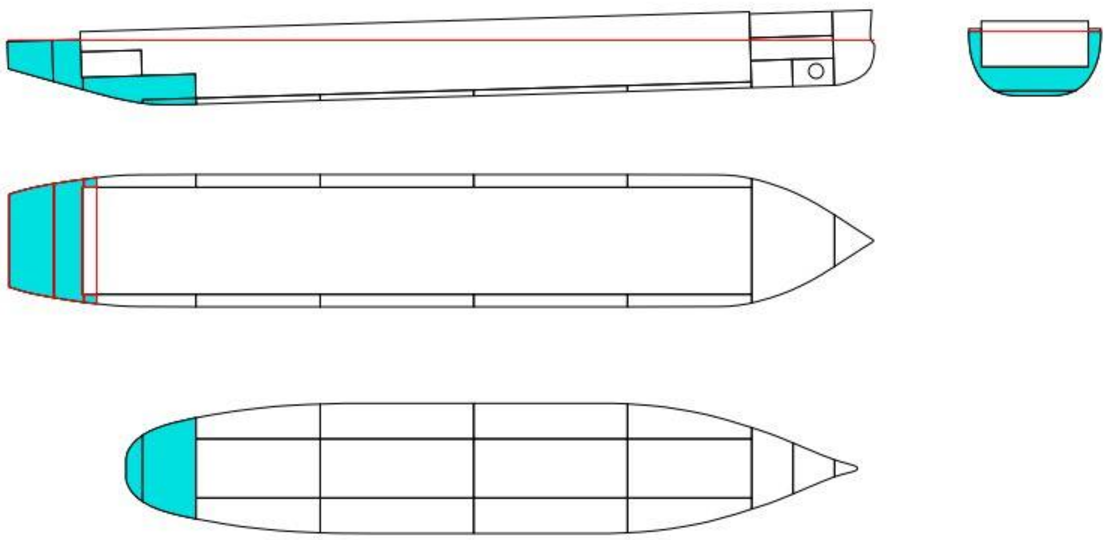


Figure 21 Floating position with large aft damage.

Figure 22 shows damaged floating position for loading condition L4 with extensive forward damage.

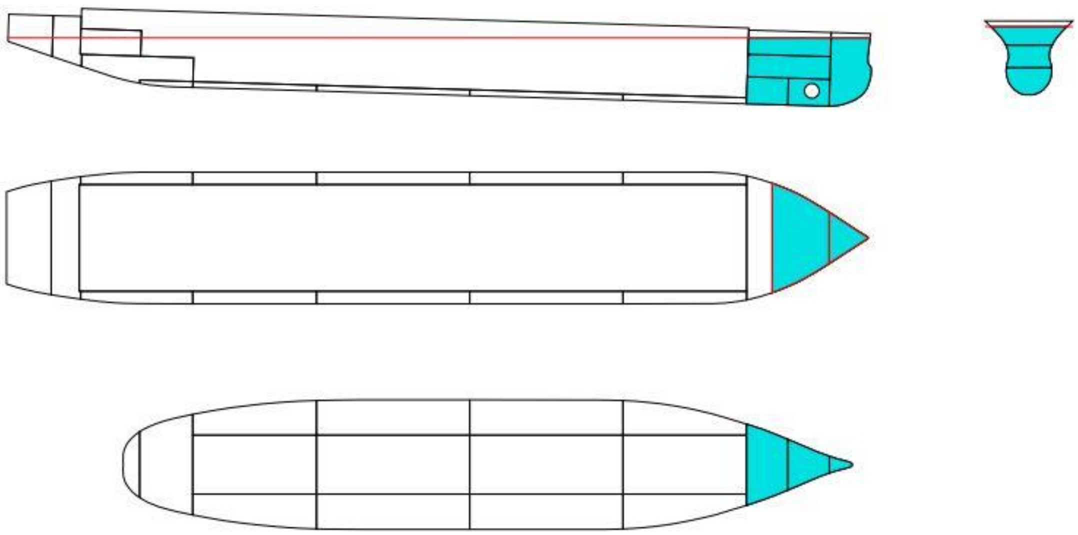


Figure 22 Floating position with large forward damage.

Figure 23 shows damaged floating position for loading condition L4 when port side ballast tanks T40P and T41P are damaged, heeling 7.5 degrees.

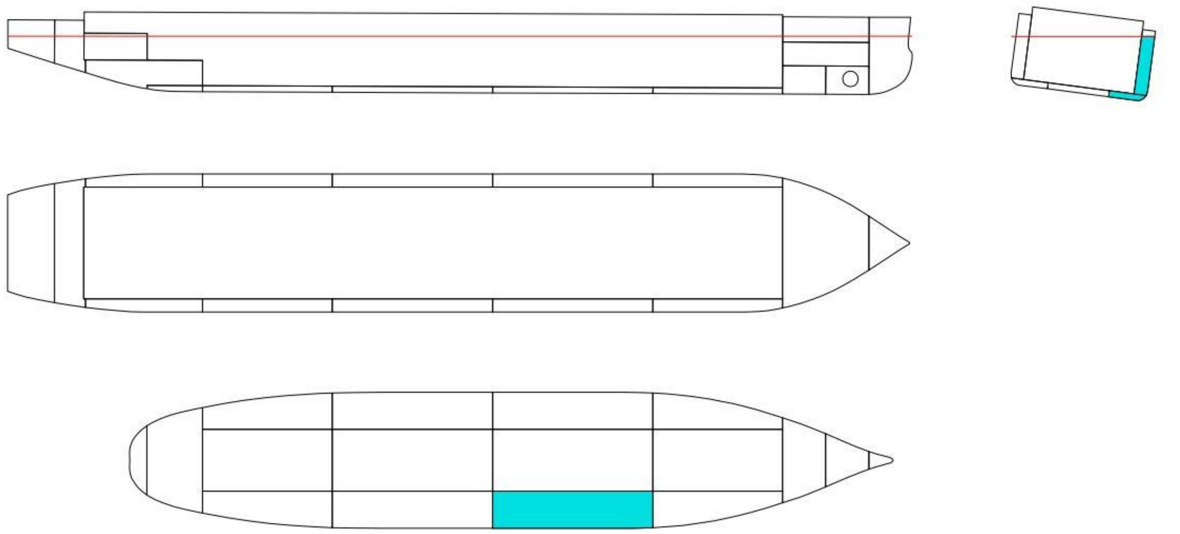


Figure 23 Floating position with side and bottom ballast tank damaged, heel 7.5 deg.

Damaged GZ-curve for loading condition L4, Grain load, when ballast tanks T40P and T41P are damaged, heeling 7.5 degrees, GZ-max 0.31 m, vertical marks at 18 degrees heel where cargo hold floods are show in Figure 24.

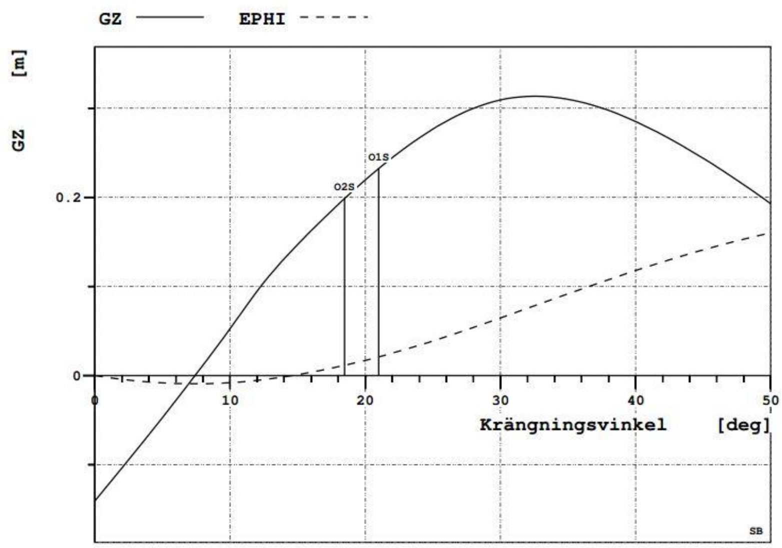


Figure 24 GZ-curve wit side and bottom ballast tank damaged, heel 7.5 deg.

5 Hydrodynamics

5.1 Hull shape

A hull form has been developed for the concept vessel, see Figure 25. This hull is designed with the main goals of low resistance and large cargo carrying capacities. The vessels speed is low, especially through sections of the Göta älv-river with speed restrictions. The benefits of a bulb to reduce resistance might be questioned for the low speeds. A small integrated bulb was however been added to the bow in order to achieve lowest possible resistance.

The vessel is designed for two large conventional controllable pitch propellers and a single skeg.

Note: both the hull shape and power predictions are based on preliminary data and would have to be further developed for better results and accuracy.

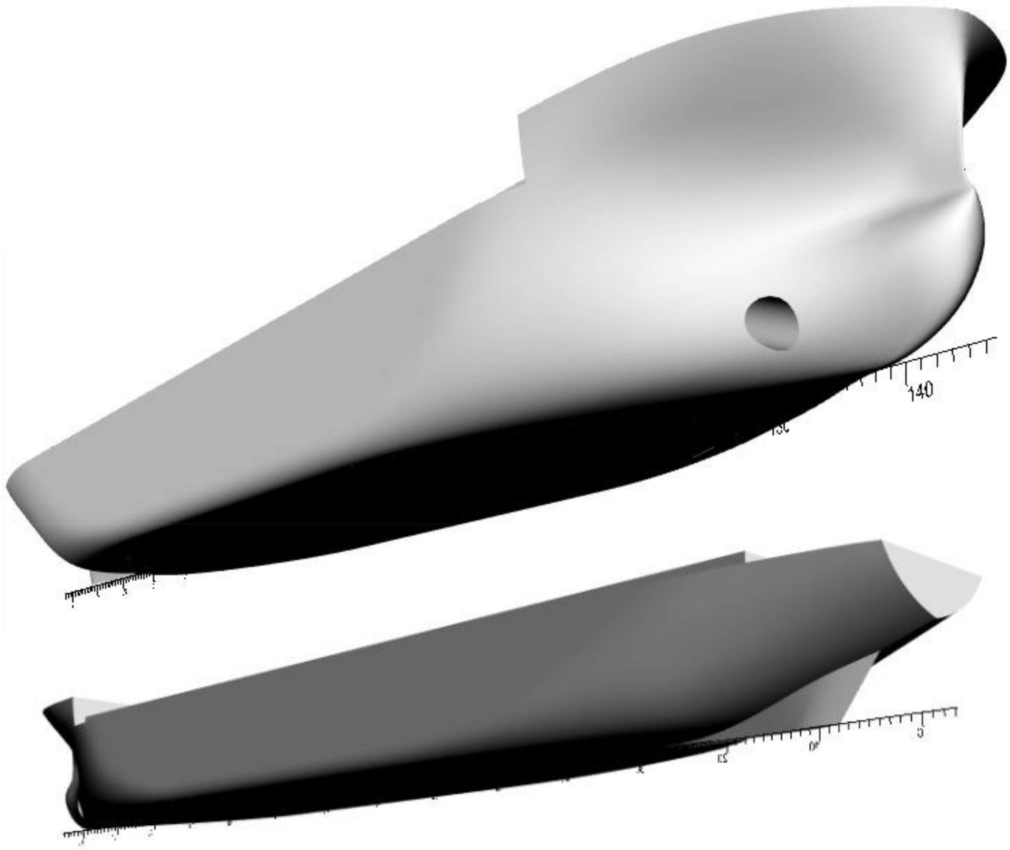


Figure 25 Hull shape of the developed vessel concept

5.2 Propulsion

The vessel is propelled by two large slow rotating propellers, see Figure 26. The propeller diameter has been maximized to achieve low propeller loading and high efficiency. The propellers are fitted to open shafts with a pair of shaft brackets. With large propellers the risk of ventilating the propellers is high when the vessel is unloaded. The amount of ballast in ballast condition is about 1 100 tons.

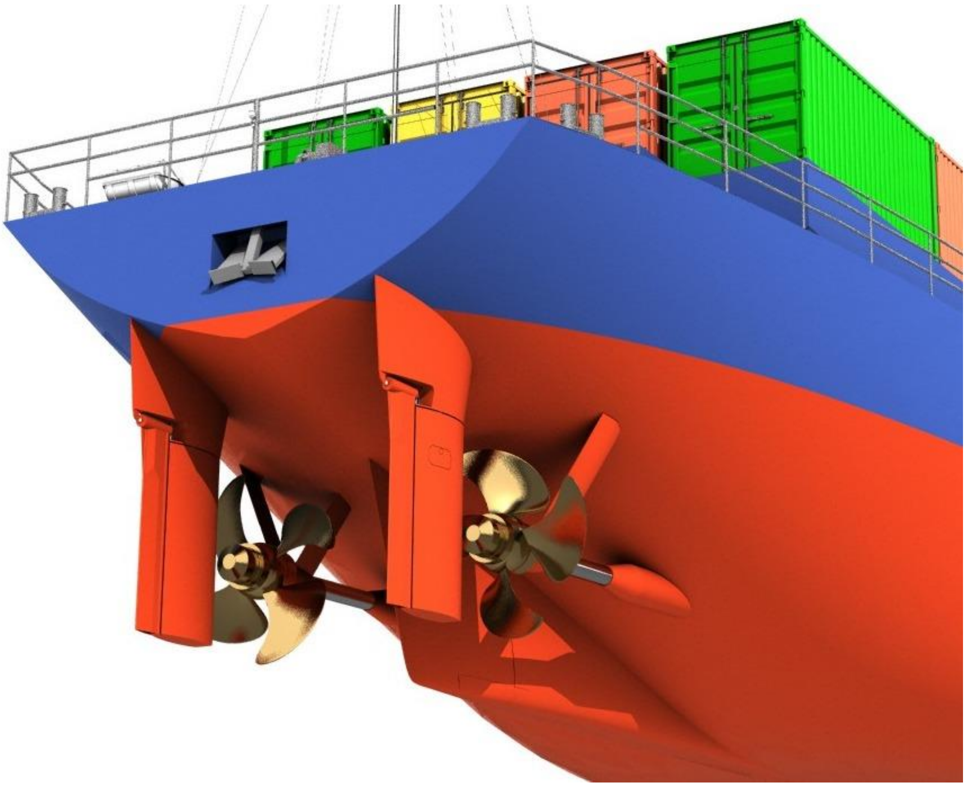


Figure 26 Propeller arrangement

Table 5 The propellers of the vessel concept

SSPA propeller series	4.53
Number of propellers	2
Propeller type	CP
Diameter [m]	3
P/D (mean) [-]	1.07
AO/AD [-]	0.53
Number of blades	4
Shaft losses	1.0 %

The vessel is fitted with two 4.5 m^2 flap-rudders for good manoeuvrability. Azimuth thrusters could be a viable option, combining both propulsion and manoeuvring, but was abandoned due to better efficiency of conventional propellers.

5.3 Power prediction

A power prediction has been made with SSPA's internal power prediction methods. The SSPA speed power prediction software is based on both SSPA systematic series and on SSPA's database of vessels tested in the towing tank.

As a first step, an accurate selection of vessels with similar non-dimensional parameters and main dimensions is carried out. SSPA's database is used to establish efficiencies and other parameters to determine a preliminary resistance and self-propulsion characteristics for the new vessel.

As a second step, the software adjust these characteristics, using the SSPA systematic series, to take into account the differences in non-dimensional parameters of the new vessel in comparison with the vessels selection carried out in the first step.

The result of the power prediction is shown in Table 6 and Figure 27 below.

Table 6 Vessels power prediction

	Trial	**Service - 15% sea margin**
Ship speed VS [kn]	Deliv. power PDT [MW]	Deliv. power PD [MW]
8	0.24	0.28
9	0.35	0.4
10	0.48	0.55
11	0.64	0.73
12	0.9	1.04
13	1.37	1.58

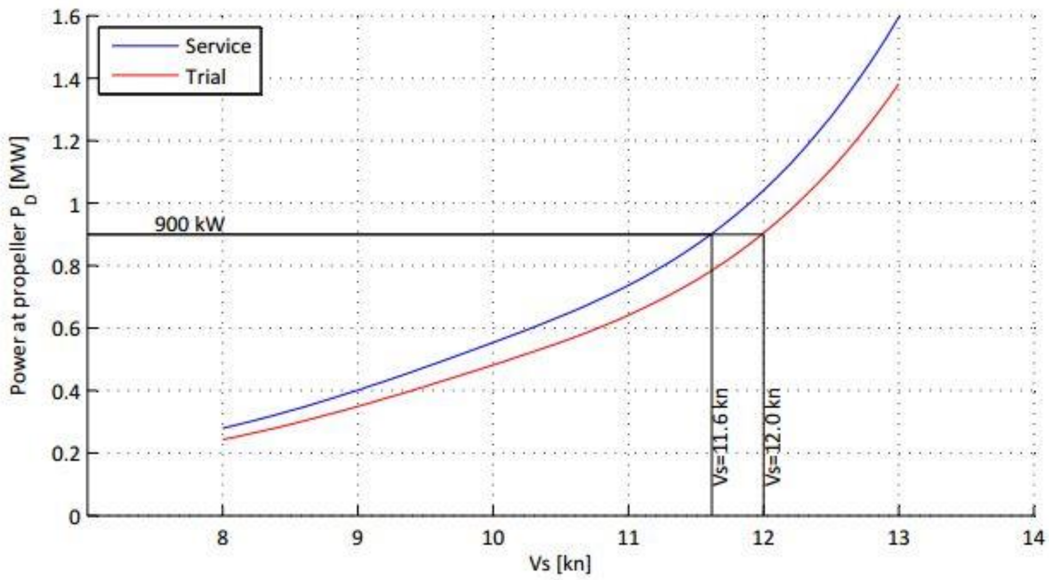


Figure 27 Power prediction, with and without 15 % sea margin

5.4 Ice class

The traffic on Lake Vänern is subject to special ice class requirements. They are denominated 1BV and 1CV. 1BV is the higher one and corresponds well to Swedish/Finnish ice class 1C, regarding propulsive power. Hull strength is not regulated in 1BV, as it is in 1C. Ice class 1C makes the ship more versatile than 1BV, and the hull reinforcements necessary to achieve ice class 1C are of low cost, therefore ice class 1C is chosen. The minimum ice requirement for Lake Vänern is 1 MW propulsion power, as for ice class 1C.

Added ice resistance has not been calculated for a prolonged journey across Lake Vänern when travelling in a broken ice channel – this could be performed if additional analysis is performed.

For the vessel to have the right of icebreaking assistance in Lake Vänern the tonnage must be larger than 2000 for ice class 1C. The vessels tonnage is 2 136.

The 1 MW engine power required for traffic in Lake Vänern will make the vessel reach a 12 kn. top speed.

5.5 Battery power and genset

The vessel will be fully powered by batteries when travelling on Göta älv. The dimensioning case is going upstream/north – using the speed/power tables described in chapter 5.3 and the time table in chapter 3. The vessel is estimated to need a battery with the capacity of between 6.1 to 6.4 MWh. This also includes the need for extra power from the counter current and squat.

The battery-pack is estimated to weigh between 40 to 90 tons including racks and cables. The lower weight is for light weight air-cooled batteries which are a viable concept for this vessel due to the very low C-rates at both charging and operational discharging. The calculated max C-rate at charging is 0.1 (which depends on how much power that can be used for charging from shore) and the C-rate when the vessel is going upstream is calculated as maximum 0.20. The cost of the batteries is estimated to be between 34 and 44 MSEK. (3.2 to 4.2 M Euro)

The concept will also be carrying a small diesel generator set – this is a result from the requirement to have the ability to cross the Lake Vänern. The generator set can be used as a range extender and for additional power in iced conditions. The size of the generator set is about 450-750 kW. The power would be rectified, and voltage adjusted before passing it to the main bus – this means that any choice of speed on the engine driving the generator is possible, even using a variable speed motor to increase the energy efficiency. Another technical possibility of a range extender could be a set of hydrogen fuel cells.

Batteries for propulsion are fitted in a compartment above the engine room. The compartment is merely intended for batteries. Installation of large batteries require additional fittings like A60 fire insulation, special ventilation arrangements, heating and chilling arrangements. Battery rooms shall also be fitted with fire detection systems and fire extinguishing systems. In order to allow for redundancy the battery room is divided into two separate rooms.

When using batteries for propulsion power there is a risk of thermal runaway. A thermal runaway is a result of the batteries becoming overheated or damaged. A thermal runaway is an exothermal reaction self-sustained from the battery itself. If a thermal runaway occurs the temperature in the battery will rise quickly and may lead to release of explosive and toxic gases. A thermal runaway could be caused by abuse of the battery. This could be overcharging, discharging too much or by physical damage.

Battery rooms must be fire insulated, to protect other spaces of the ship and to protect the batteries from fire in neighbouring compartments. Further, a battery room must be fitted with a ventilation system that ventilates toxic or explosive gases that might be released in case of a thermal runaway. This ventilation system is a battery room specific system and cannot be connected to the ship's ordinary ventilation system. Ventilation of the battery rooms would be through the extension of the cargo hold coamings, which form the walls of the battery rooms to the sides of the ship.

An efficient way of avoiding batteries being overheated is to control the battery temperature. This can be made by an air- or water-cooling system. The temperature of the batteries is not constant when in use. During charging or heavy discharging the temperature might rise. If the temperature is allowed to rise too much it might be an initiation of a thermal runaway. Control of battery temperature is therefore essential. A cooling system can also be used for keeping the temperature of batteries up in cold climate. Batteries have a temperature comfort zone for best battery performance.

Figure 28 Example of battery installation on a passenger ferry (source: SSPA/Västtrafik)

The space needed for the 6 100 kWh batteries is about 230 m^3. This includes storage racks for keeping the batteries fixed, cooling and heating systems, fire extinguishing systems and ventilation systems mentioned above. The space for holding the batteries is shown in green in Figure 29 below.

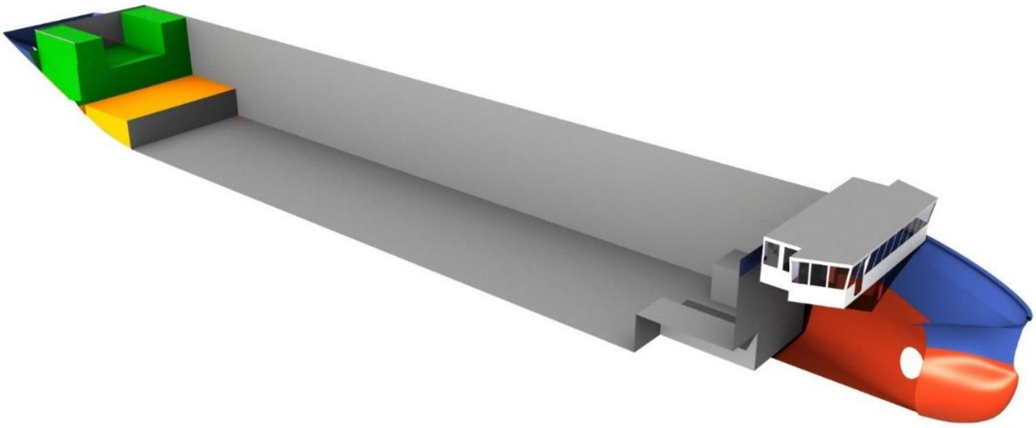


Figure 29 Space required for batteries, in green, engine room in yellow

The space required for the battery installation can be compared to volumes of TEUs. The space is about the same volume as six TEUs. This is cargo carrying capacity that is lost due to electric battery propulsion. The batteries cannot be stored in awkward spaces difficult to use for other purposes, as can be done with diesel oil.

One analysed idea was to store the batteries in TEUs, as on Stena Jutlandica, see Figure 30. These containers could be exchanged to similar containers with fully charged batteries when at port. In such a case, the vessel would not need to stay in port for longer periods to charge the batteries, although the large investment cost for batteries would be tripled. However, connecting the battery-containers with cables for electric power, data communication-cables, pipes for cooling and pipes for exhaust ventilation when shifting battery containers will probably not be made easily.

Figure 30 Large container for batteries on Stena Jutlandica (source: www.stena.com)

Since the vessel need to stay in port for several hours to load and unload all containers there will be enough time for charging the batteries on board. The idea of stowing batteries in their own containers was therefore abandoned for the inland waterway vessel concept.

5.6 Engine arrangement

The propulsion system is divided into two independent propulsion lines. Each consists of one electric motor of 590 kW @ 1200 rpm, driving a fixed controllable pitch propeller, SSPA 4.53, through a two step planetary gear box with a 9:1 reduction. The motors are reluctance assisted permanent magnet motors, with high efficiency and torque. The engine arrangement has a low height and only requires one standard deck height of 2.8 m above the double bottom. Two high lift rudders of 4.5 m² provide good manoeuvrability and the possibility to generate close to 90° thrust. An electric bow thruster of 180 kW is installed for port manoeuvres and to assist turning in tight river bends.

The propulsion system is divided into two independent propulsion lines. Each consists of one electric motor of 590 kW @ 1200 rpm, driving a controllable pitch propeller, SSPA 4.53, through a gearbox with a 9:1 reduction. The reduction gear is a two-step planetary gear box. The motors are reluctance assisted permanent magnet motors, with high efficiency and for their size high torque. The engine arrangement has a low height and only requires one standard deck height of 2.8 m above the double bottom. Two high lift rudders of 4.5 m² provide good manoeuvrability and the possibility to generate close to 90° thrust. An electric bow thruster of 180 kW is installed for port and lock manoeuvres and to assist turning in tight river bends.

The battery and engine rooms are both separated into two identical rooms, see Figure 31 and 32. Each with a fire and watertight integrity in order to maximise the vessels propulsion redundancy in case of fire or water ingress. Access to the engine and battery rooms are through a staircase in the centreline.

Figure 31 The battery room and the generator room.

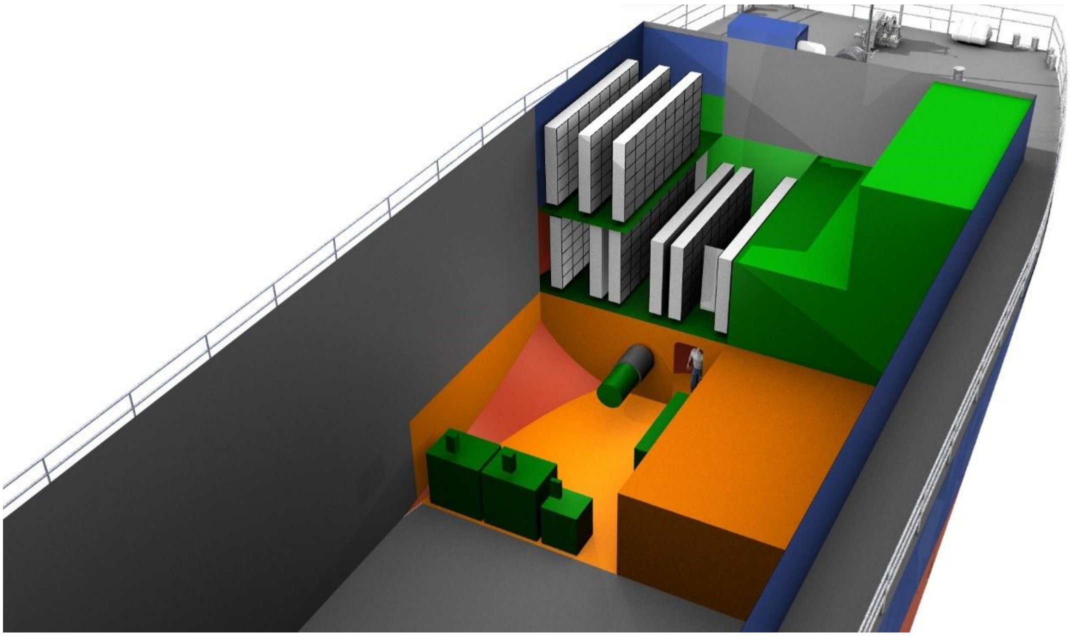


Figure 32 Cut-out view of the starboard engine room, battery room and the generator room.

6 Energy requirements

The basis of the capacity calculation for the batteries installed is that the ship shall be able to perform a one-way trip between Gothenburg and Trollhättan, upstream with the maximum head current. The speed shall be the maximum speed allowed, which varies between 5 and 10 knots along Göta älv. The squat-effect from shallow water is also taken into account. The average load from other consumers than propulsion is estimated to be 30 to 50 kW. The total efficiency of inverters, motors, gearing and shafts is estimated to be 88 %, whilst the efficiency for the provision of the hotel load is estimated to be 95 %.

The result of the energy calculations is that between 4 290 and 4 450 kWh electrical energy is required from the batteries when going upriver and between 2 640 and 2 800 kWh when going down river. Using 70 % of the battery capacity, for longer battery life, means that the required battery capacity is between 6 100 and 6 350 kWh when going upriver and between 3 770 and 4 000 kWh when going downriver. The required energy to fully charge the batteries is between 4 370 to 4 540 kWh after a journey upriver and between 2 700 to 2 860 kWh downriver.

The chosen battery size is 6 100 kWh, this is due to the very low C-rates at operation (0,20 max) and charging (0.11 after a trip upriver) and few charge cycles over the battery life. Please note that the required battery size is highly dependent on particularities in the cell chemistry. Some cell chemistries may require a smaller battery size – it is however believed that none will require a larger size than what is used here.

Using 4 hours for charging mean that the needed charge power is between 1 095 and 1 135 kW when charging upstream and between 675 and 715 kW when charging downstream. On top of this the hotel load is added giving a total shore connection power of 1 125 to 1 165 kW in Trollhättan and between 705 to 745 kW in Gothenburg. Longer charging time would lower the need for charging power.

7 Conclusions

This project has developed an electrified inland waterway vessel concept for dedicated operations on Göta älv, between Port of Gothenburg and Trollhättan port. The vessels main particulars are specified in Figure 33.

Main particular	Specification
LOA	87.9 m
L_{WL}	87.7 m
B_M	13.4 m
D	6.9 m
T_M	4.4 m
T_{max}	5.35 m
$T_{Ball.}$	3.0 m
Air draught	6.15 m / 18.7 m
DW	3 475 ton
Ballast	1 306 m^3
Loading container capacity	160 TEU or 70 FEU + 20 TEU
Hold capacity	4 884 m^3/ 172 500 cub. ft.
Hold dimensions	L 68 m B 10.85 m D 7.1 m
Grain	3 475 ton
Timber cap.	2 048 ton
Gross tonnage	2 136
Net tonnage	1 310
Hatches	No
Speed serv.	10 kn.
Speed max	12 kn.
Battery amt.	6 100 kWh
Endurance	50 Nm
Machinery	Battery Electric
Propellers	2 x 3.0 , CP
Crew	3
Bow thrust.	180 kW
Ice class	1C

Figure 33 Vessel main particulars

The vessel is developed for the largest possible size, with special permission for passage through the locks in Trollhättan, being able to carry 160 TEUs.

Transport of containers on the river Göta älv with an entirely battery electric propelled inland waterway vessel is possible. The vessel would be a pure zero-emission vessel. The space required to fit the 6 100 kWh batteries can be compared to the volume of six TEUs. The batteries can be charged and discharged at low rates enabling for a long battery lifetime. Battery charging power at end terminals are quite low.

As an inland waterway vessel, the vessel cannot make voyages outside of the IWW-zones. Powered with batteries the vessel also has a limited reach. Other possible routes connected to Göta älv is on Vänern and on newly regulated coastal zones north of Gothenburg. Also, other Swedish IWW-zones on the south and eastern coast of Sweden, as well as lake Mälaren, could be possible to operate.

The vessel concept is possible to operate for five roundtrips/week between Gothenburg and Trollhättan. If fully loaded with TEUs, the target of being capable of doing a return trip in 24 hours will be difficult to meet, which depends on the loading and unloading capacity in Gothenburg and Trollhättan port.

The cost of the battery equipment is estimated to be about 34 to 44 MSEK, about 3.6 to 4.6 M Euro. The additional cost for battery electric propulsion is thereby large compared to the price of an ordinary diesel propelled inland waterway vessel. A full life cycle cost of the developed vessel is needed to better understand the business opportunities of realising such a concept.

Appendices:

Appendix 1. Stability calculations

Appendix 2. Data from lock passage analysis

Loading condition: L1 Containers 134 TEU, No Ball.

Tank contents listed after GZ-curve.

Fixed weights	Weight [t]	CG fr. AP [m]	CG fr. CL [m]	CG fr. BL [m]	Free.surf [tm]
Containers	1902.80	44.50	0.00	5.32	0.00
Fixed weights	1902.80	44.50	0.00	5.32	0.00

Total weights	Weight [t]	CG fr. AP [m]	CG fr. CL [m]	CG fr. BL [m]	Free.surf [tm]
Deadweight	1902.80	44.50	0.00	5.32	0.00
Lightweight	1520.00	43.50	0.00	5.52	
Total	3422.80	44.06	5.41	0.00	

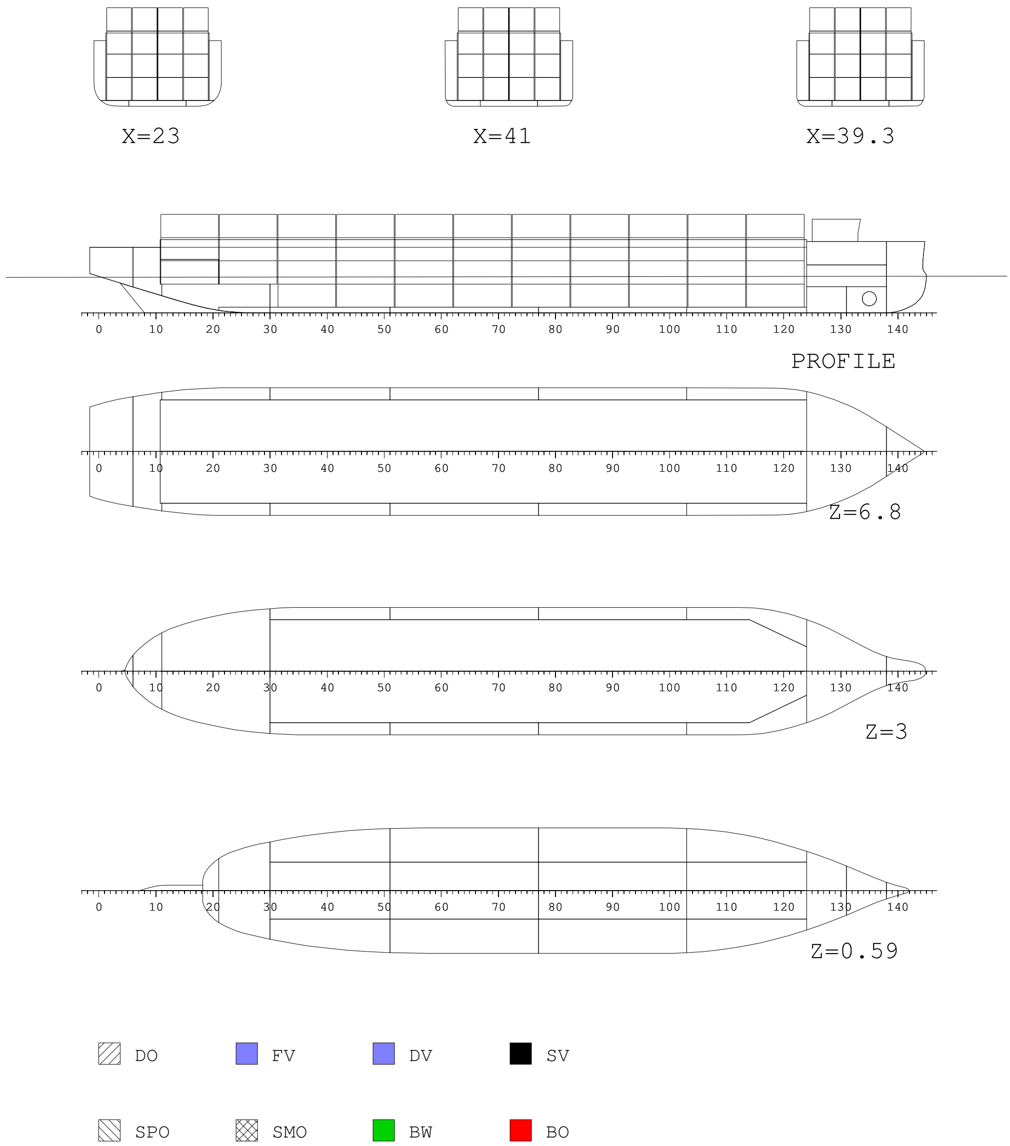
	Intaktstabilitet SSPA IWTS	2019-12-23 USER SS IWTS19:1

Loading condition: L1 Containers 134 TEU, No Ball.

Floating position

Mean draught., Tm:	3.81 m	KM:	5.92 m
Trim:	0.13 m	KG:	5.41 m
Draught, fore, Tf:	3.87 m	GM0:	0.51 m
Draught, aft, Ta:	3.75 m	GMkorr:	0.00 m
Heel:	0.00 gr	GM:	0.51 m

Floating position and weight positions

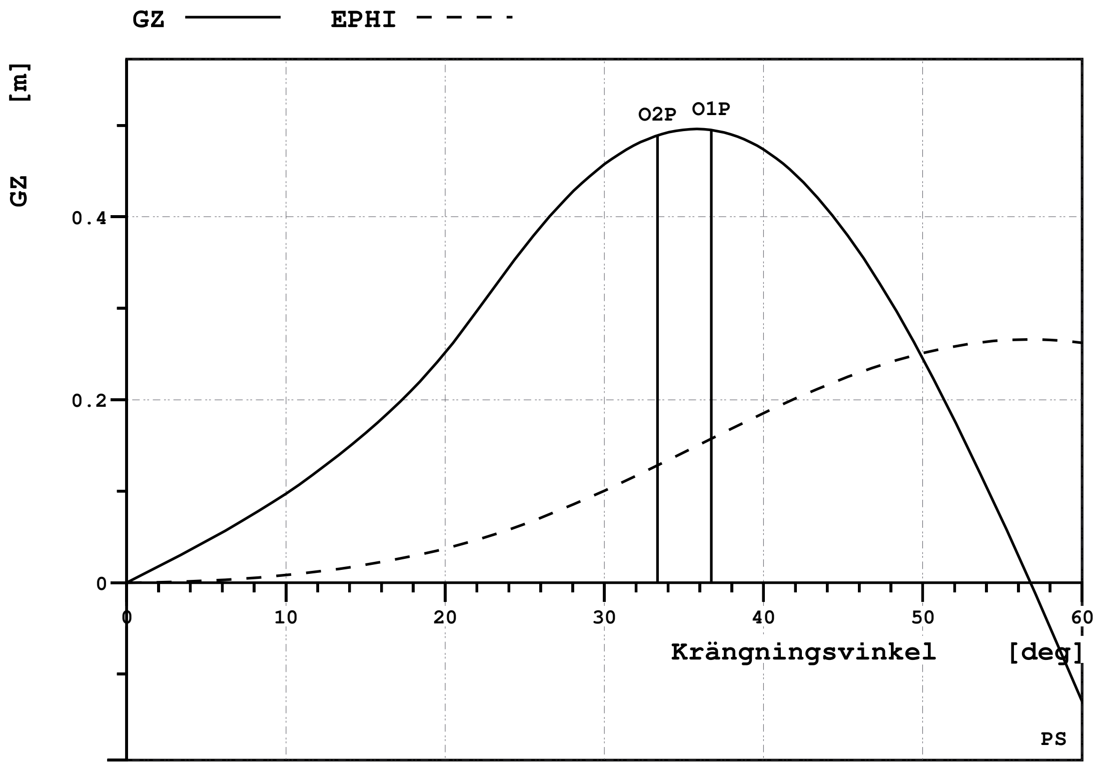


Loading condition: L1 Containers 134 TEU, No Ball.

GZ-data

HEEL	[deg]	-	0.0	10.0	20.0	25.0	30.0	40.0	50.0	60.0
GZ	[m]	-	0.000	0.097	0.251	0.367	0.457	0.473	0.245	-0.130
AREA	mrad	-	0.000	0.008	0.037	0.064	0.100	0.185	0.251	0.262

GZ-curve



Stability criteria IWW	Req.	Value	Enhet	status
Residual safety clearance > 0 mm	0.000	2.341	m	OK
GM > 0.5 m	0.500	0.506	m	OK

Stabilitetskrav IMO	Req.	Value	Enhet	status
Area under GZ curve up to 30 deg.	0.055	0.100	mrad	OK
Area under GZ curve up to 40 deg.	0.090	0.128	mrad	OK
Area under GZ curve btw. 30-40 deg.	0.030	0.028	mrad	NOT MET
Max GZ > 0.2	0.200	0.496	m	OK
Max. GZ at an angle > 25 deg.	25.000	35.776	deg	OK

Critical flooding openings

OPENING	X [m]	Y [m]	Z [m]	FLOODING [deg]	DIST.AB.WL [m]
O2P	74.400	5.425	7.500	33.4	3.6
O1P	18.000	5.425	7.500	36.7	3.7
O1S	18.000	-5.425	7.500	-	3.7

Lastfall: L1 Containers 134 TEU, No Ball.

Tank content:

Loading condition: L3B Containers 160 TEU + Ball

Tank contents listed after GZ-curve.

Fixed weights	Weight [t]	CG fr. AP [m]	CG fr. CL [m]	CG fr. BL [m]	Free.surf [tm]
Containers	2272.00	40.05	0.00	5.94	0.00
Fixed weights	2272.00	40.05	0.00	5.94	0.00

Tank content	Weight [t]	CG fr. AP [m]	CG fr. CL [m]	CG fr. BL [m]	Free.surf [tm]
Ballast water	647.63	52.60	0.00	1.20	9.07
Tank content	647.63	52.60	0.00	1.20	9.07

Total weights	Weight [t]	CG fr. AP [m]	CG fr. CL [m]	CG fr. BL [m]	Free.surf [tm]
Deadweight	2919.63	42.83	0.00	4.89	9.07
Lightweight	1520.00	43.50	0.00	5.52	
Total	4439.63	43.06	5.11	9.07	

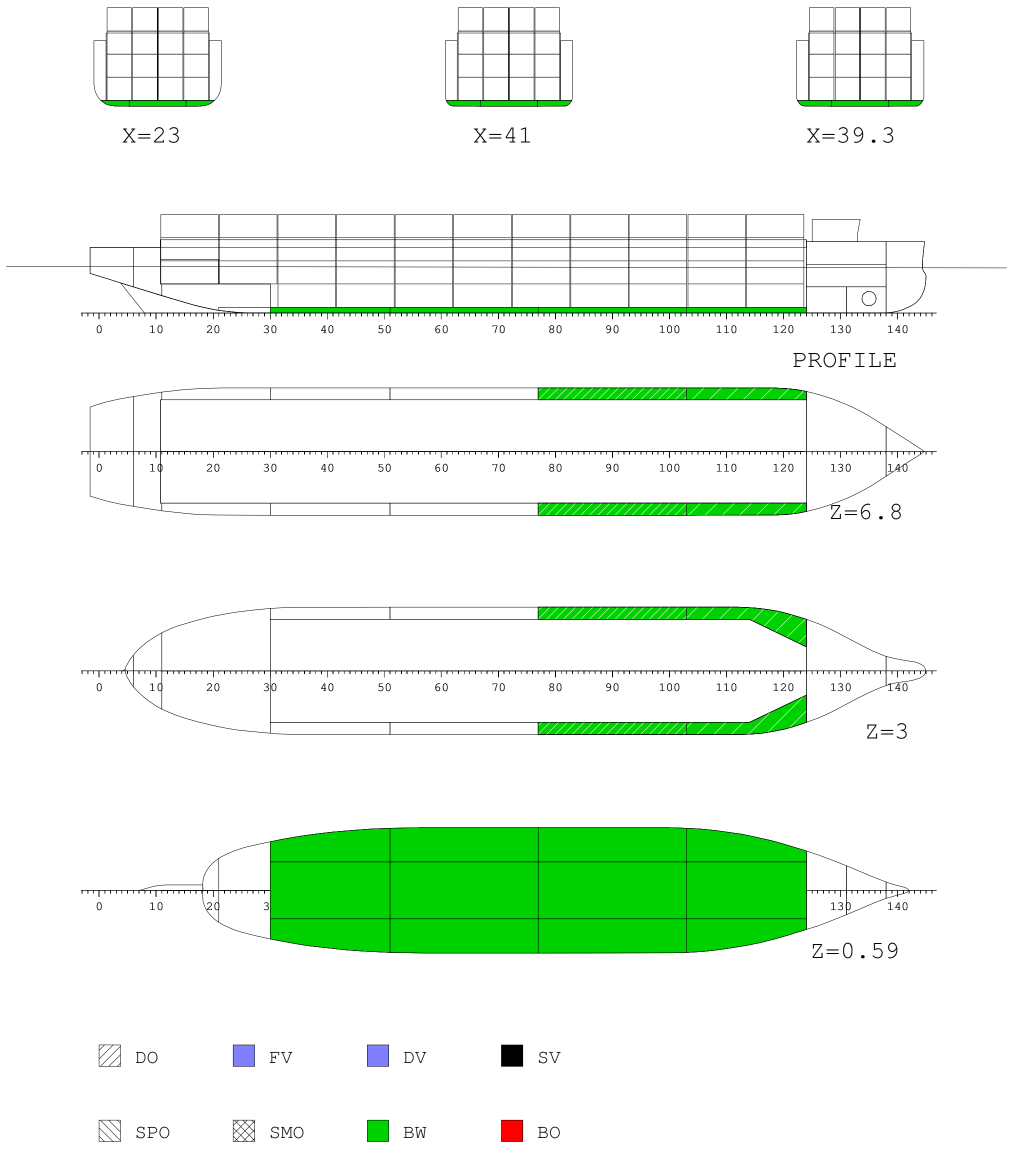
	Intaktstabilitet SSPA IWTS	2019-12-23 USER SS IWTS19:1

Loading condition: L3B Containers 160 TEU + Ball

Floating position

Mean draught., Tm:	4.81 m	KM:	5.69 m
Trim:	-0.15 m	KG:	5.11 m
Draught, fore, Tf:	4.74 m	GM0:	0.59 m
Draught, aft, Ta:	4.88 m	GMkorr:	0.00 m
Heel:	0.00 gr	GM:	0.59 m

Floating position and weight positions

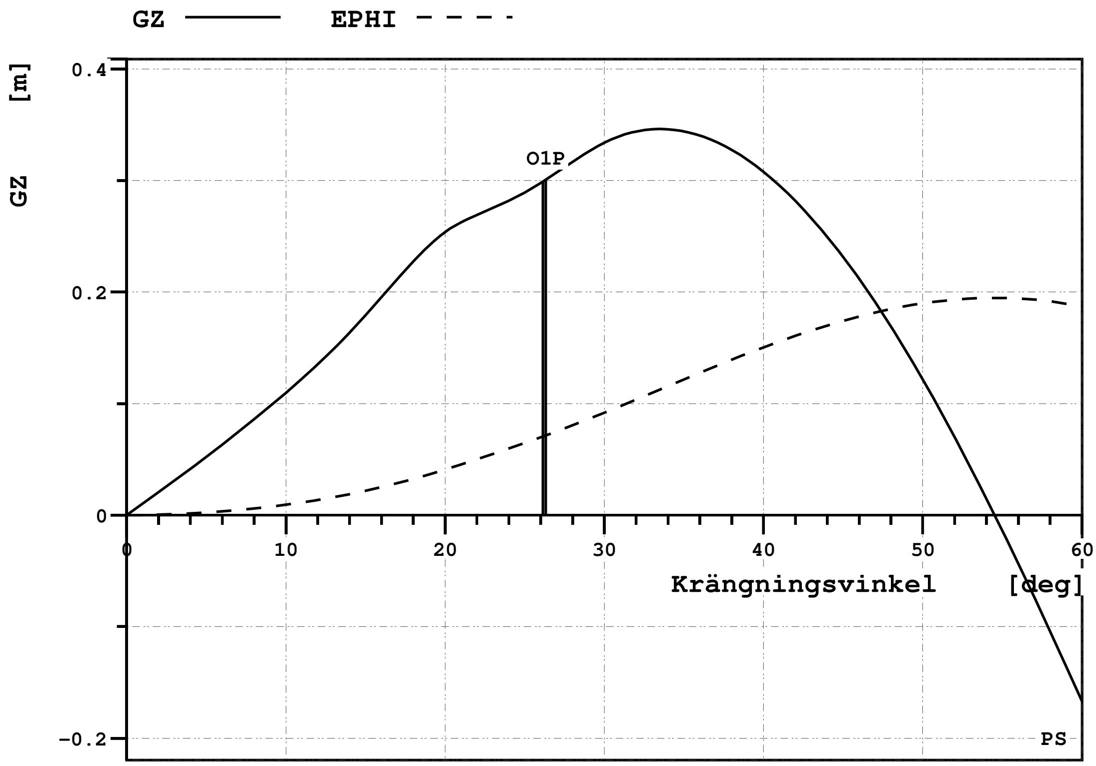


Loading condition: L3B Containers 160 TEU + Ball

GZ-data

HEEL	[deg]	-	0.0	10.0	20.0	25.0	30.0	40.0	50.0	60.0
GZ	[m]	-	0.000	0.110	0.254	0.289	0.334	0.308	0.122	-0.167
AREA	mrad	-	0.000	0.009	0.041	0.065	0.092	0.151	0.190	0.187

GZ-curve



Stability criteria IWW	Req.	Value	Enhet	status
Residual safety clearance > 0 mm	0.000	1.730	m	OK
GM > 0.5 m	0.500	0.585	m	OK

Stabilitetskrav IMO	Req.	Value	Enhet	status
Area under GZ curve up to 30 deg.	0.055	0.092	mrad	OK
Area under GZ curve up to 40 deg.	0.090	0.071	mrad	NOT MET
Area under GZ curve btw. 30-40 deg.	0.030	-	mrad	NOT MET
Max GZ > 0.2	0.200	0.346	m	OK
Max. GZ at an angle > 25 deg.	25.000	33.488	deg	OK

Critical flooding openings

OPENING	X [m]	Y [m]	Z [m]	FLOODING [deg]	DIST.AB.WL [m]
O2P	74.400	5.425	7.500	26.2	2.7
O1P	18.000	5.425	7.500	26.4	2.6
O1S	18.000	-5.425	7.500	-	2.6

Lastfall: L3B Containers 160 TEU + Ball

Tank content:

Id	Description	Weight [t]	Fill [%]	CG fr. AP [m]	CG fr. CL [m]	CG fr. BL [m]	Free surf. [tm]
Ballast water (Density: 1.00 t/m3)							
T20S		18.89	100	25.02	-4.36	0.32	0.0
T20P		18.89	100	25.02	4.36	0.32	0.0
T30S		30.61	100	38.42	-4.69	0.31	0.0
T30P		30.61	100	38.42	4.69	0.31	0.0
T40S		30.68	100	53.99	-4.69	0.31	0.0
T41S		49.12	40	54.00	-6.06	1.86	2.6
T40P		30.68	100	53.99	4.69	0.31	0.0
T41P		49.12	40	54.00	6.06	1.86	2.6
T50S		16.54	100	66.84	-4.28	0.32	0.0
T51S		79.12	80	68.28	-5.61	3.00	1.9
T50P		16.54	100	66.84	4.28	0.32	0.0
T51P		79.12	80	68.28	5.61	3.00	1.9
T20C		44.22	100	24.30	0.00	0.30	0.0
T40C		54.67	100	54.00	0.00	0.30	0.0
T50C		44.16	100	68.10	0.00	0.30	0.0
T30C		54.66	100	38.40	0.00	0.30	0.0
Sum		647.63		52.60	0.00	1.20	9.1
Total		647.63		52.60	0.00	1.20	9.1

Loading condition: L4 Grain, 3475 T

Tank contents listed after GZ-curve.

Fixed weights	Weight [t]	CG fr. AP [m]	CG fr. CL [m]	CG fr. BL [m]	Free.surf [tm]
Containers	0.00	0.00	0.00	0.00	0.00
Grain Dens. 0.8	3475.20	42.80	0.00	4.15	0.00
Fixed weights	3475.20	42.80	0.00	4.15	0.00

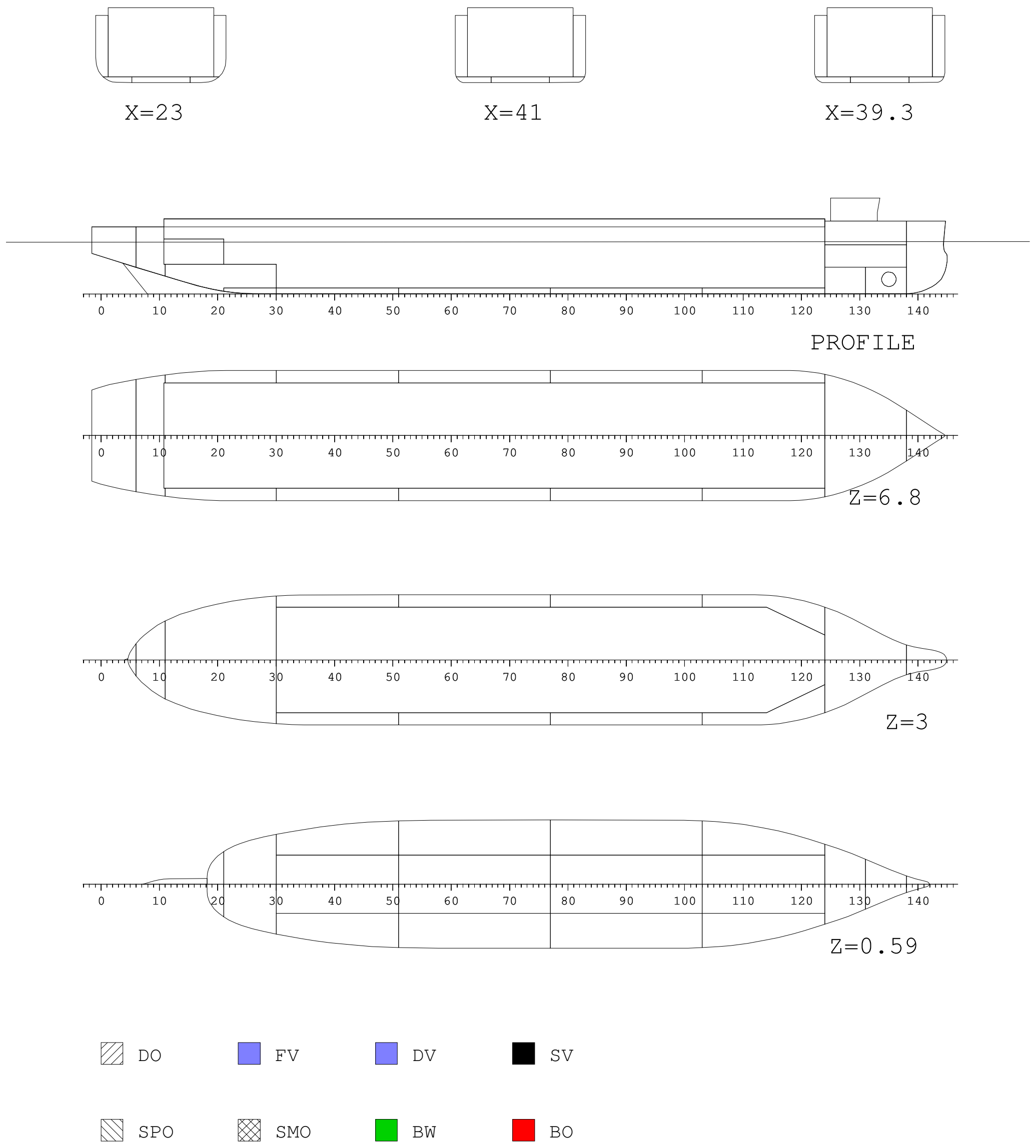
Total weights	Weight [t]	CG fr. AP [m]	CG fr. CL [m]	CG fr. BL [m]	Free.surf [tm]
Deadweight	3475.20	42.80	0.00	4.15	0.00
Lightweight	1520.00	43.50	0.00	5.52	
Total	4995.20	43.01	4.57	0.00	

Loading condition: L4 Grain, 3475 T

Floating position

Mean draught., Tm:	5.35 m	KM:	5.68 m
Trim:	0.04 m	KG:	4.57 m
Draught, fore, Tf:	5.37 m	GM0:	1.12 m
Draught, aft, Ta:	5.33 m	GMkorr:	0.00 m
Heel:	0.00 gr	GM:	1.12 m

Floating position and weight positions

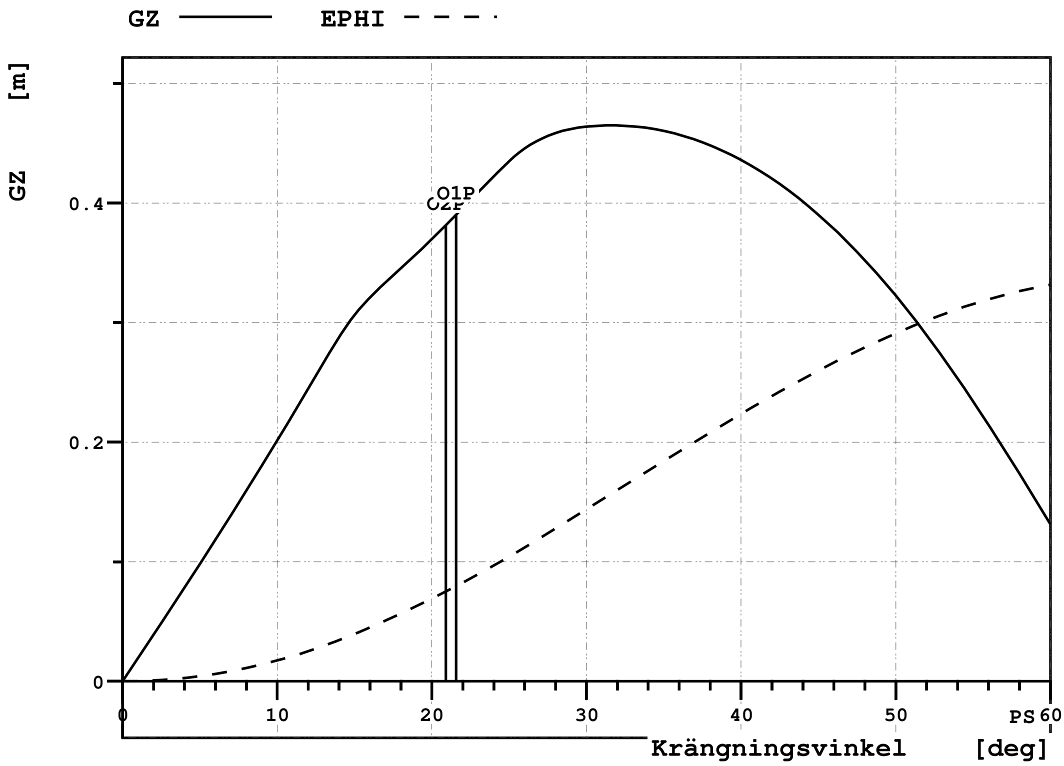


Loading condition: L4 Grain, 3475 T

GZ-data

HEEL	[deg]	-	0.0	10.0	20.0	25.0	30.0	40.0	50.0	60.0
GZ	[m]	-	0.000	0.201	0.370	0.435	0.464	0.436	0.323	0.131
AREA	mrad	-	0.000	0.018	0.068	0.104	0.143	0.223	0.290	0.331

GZ-curve



Stability criteria IWW	Req.	Value	Enhet	status
Residual safety clearance > 0 mm	0.000	1.719	m	OK
GM > 0.5 m	0.500	1.117	m	OK

Stabilitetskrav IMO	Req.	Value	Enhet	status
Area under GZ curve up to 30 deg.	0.055	0.143	mrad	OK
Area under GZ curve up to 40 deg.	0.090	0.074	mrad	NOT MET
Area under GZ curve btw. 30-40 deg.	0.030	-	mrad	NOT MET
Max GZ > 0.2	0.200	0.466	m	OK
Max. GZ at an angle > 25 deg.	25.000	32.088	deg	OK

Critical flooding openings

OPENING	X [m]	Y [m]	Z [m]	FLOODING [deg]	DIST.AB.WL [m]
O2P	74.400	5.425	7.500	20.9	2.1
O1P	18.000	5.425	7.500	21.6	2.2
O1S	18.000	-5.425	7.500	-	2.2

Lastfall: L4 Grain, 3475 T

Tank content:

Uppgjord (även faktaansv. om annan) ***Prepared*** *(also subject resp. if other)*	**Titel** *Title*	**Dok Nr.** *Doc No*	
Martin Borgh		RE41178514-05-00-A	
Dokumentansvarig / Godkänd ***Document*** *responsible / Approved*	**Filnamn** *Filename*	**Datum** *Date*	Rev
MBO	Appendix 2	2020-06-22	3

The time passing through the locks in Lilla Edet and Trollhättan has been determined after an analysis of AIS data for all vessels passing the locks over one full year (2018). The lines set for entry and exit of the locks are shown in the two following figures.

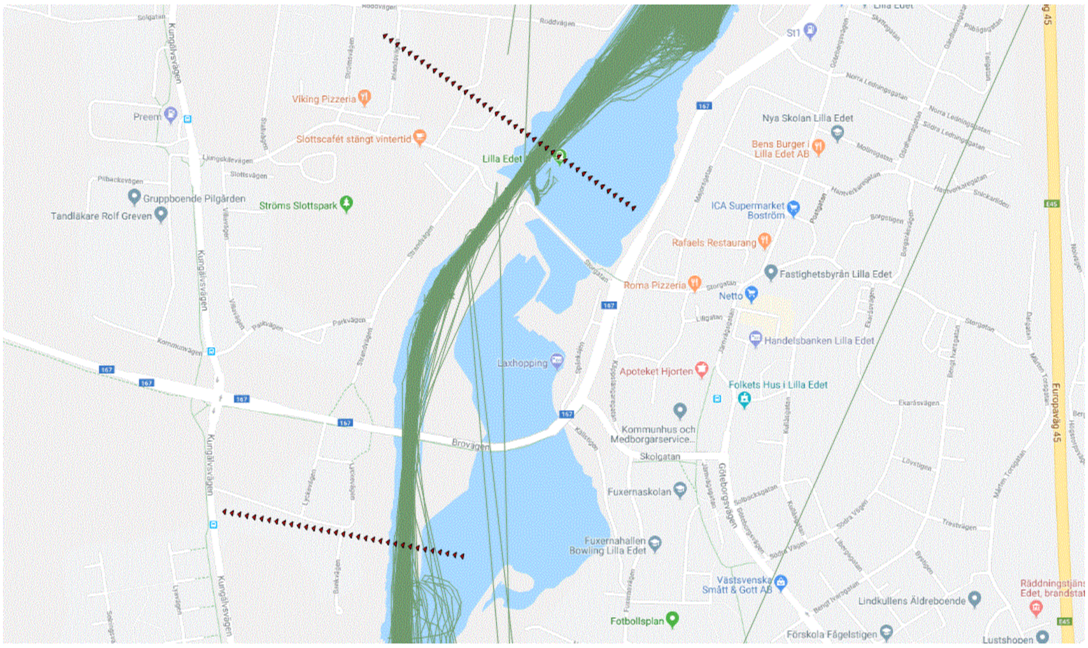


Figure 1: Lines defining entry and exit through locks in Lilla Edet.

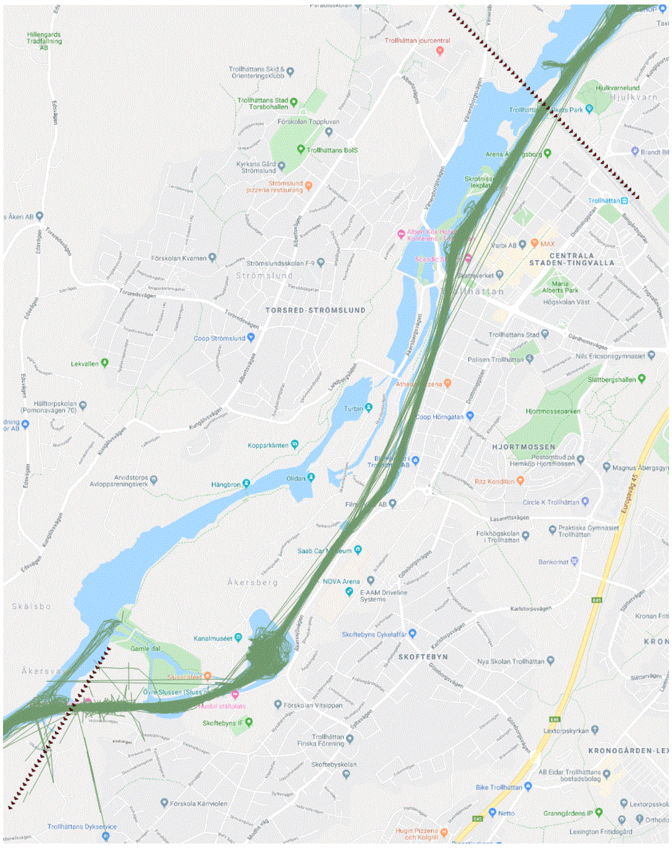


Figure 2: Lines defining entry and exit through locks in Trollhättan.

1.1.1 AIS data for passage through Lilla Edet lock

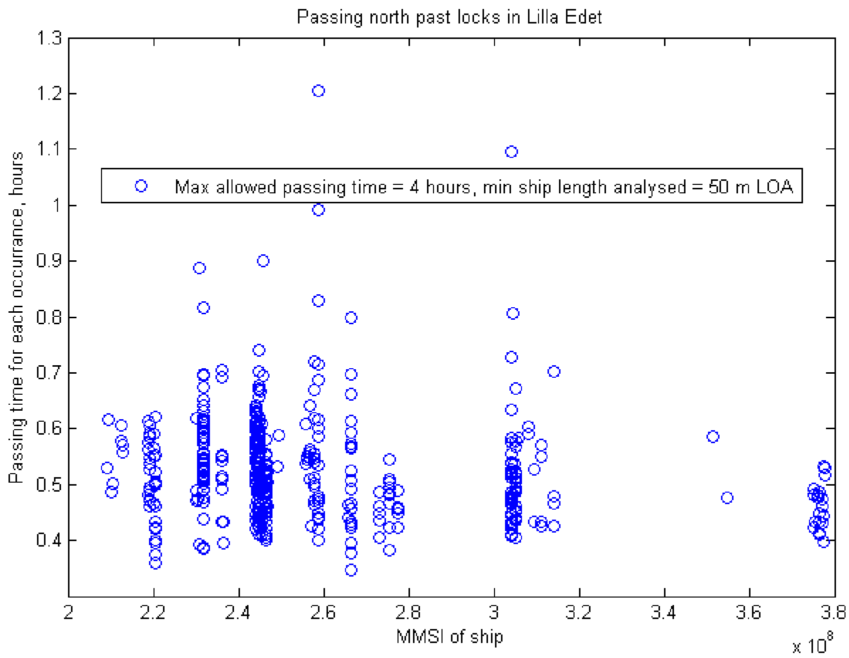


Figure 3: Data of all passages through Lilla Edet locks going north (ships with LOA above 50 m)

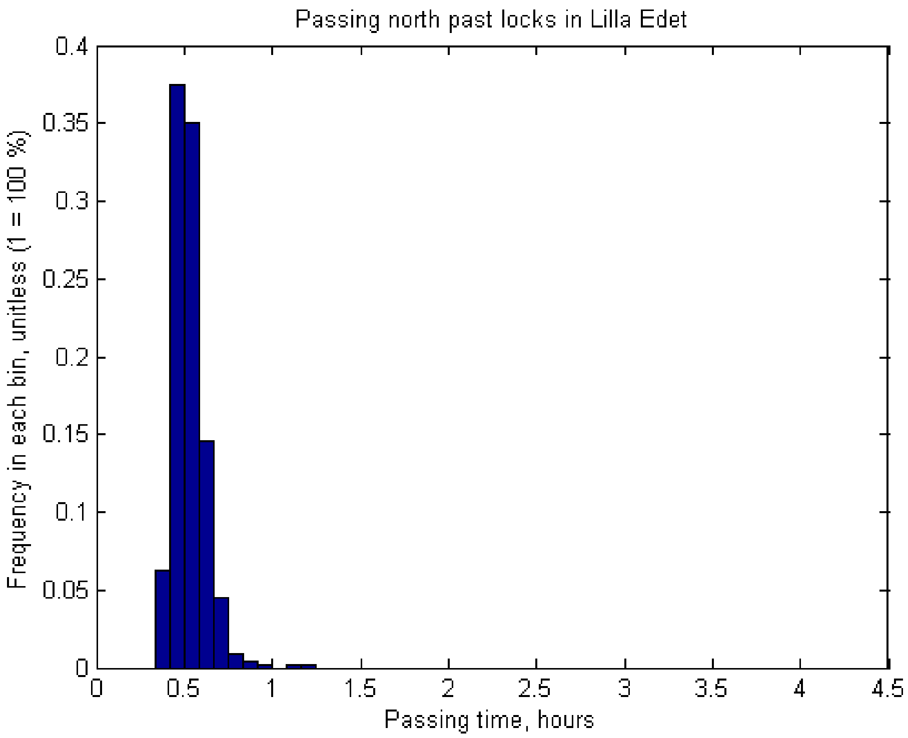


Figure 4: Frequency function of passages through Lilla Edet locks going north, 5 minute time resolution (bins).

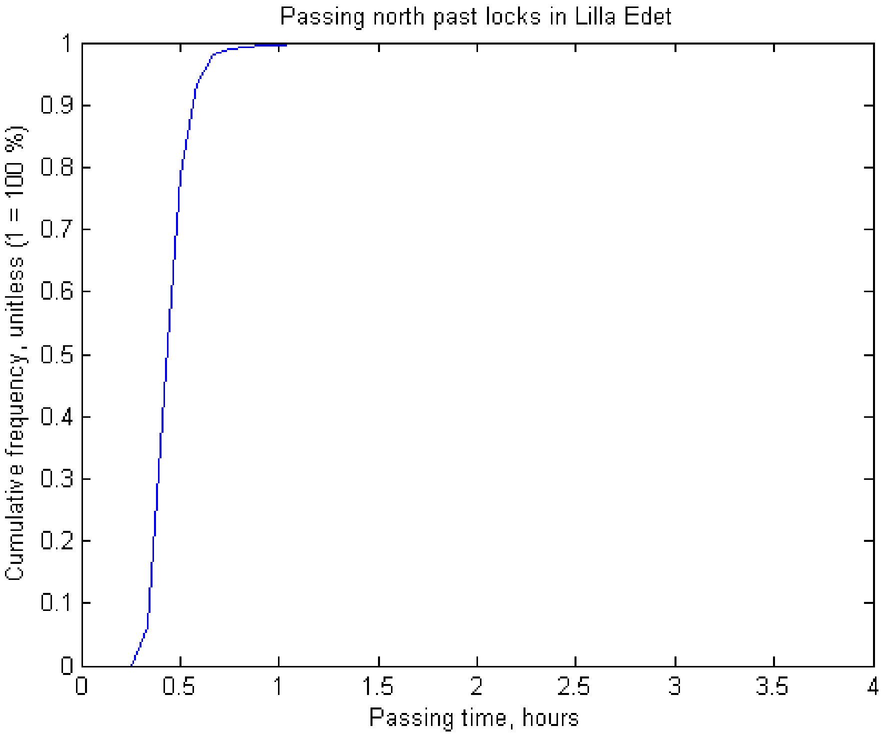


Figure 5: Cumulative distribution of passages through Lilla Edet locks going north, 5 minute time resolution (bins).

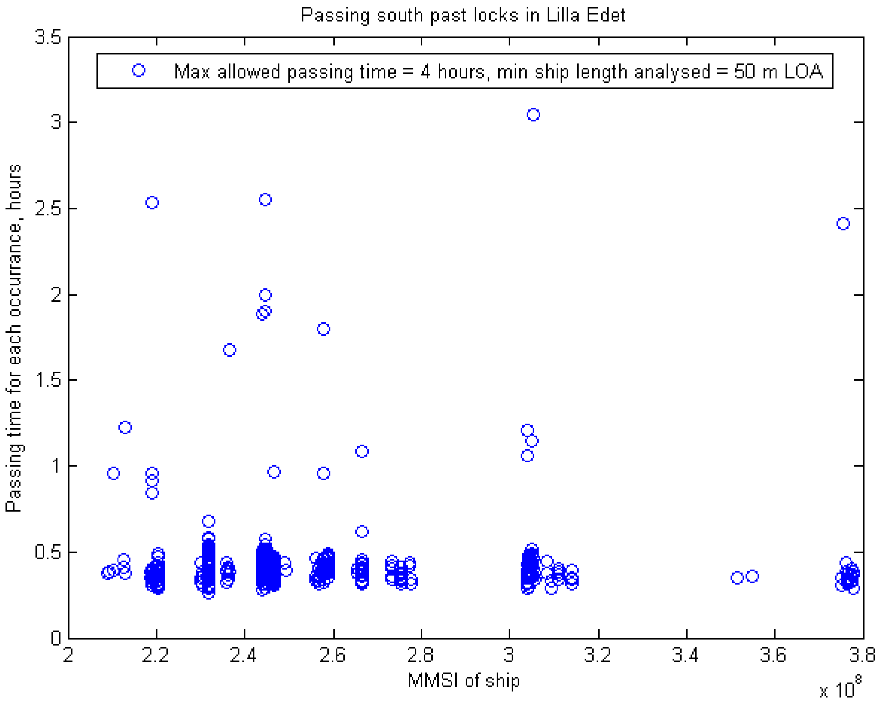


Figure 6: Data of all passages through Lilla Edet locks going south (ships with LOA above 50 m)

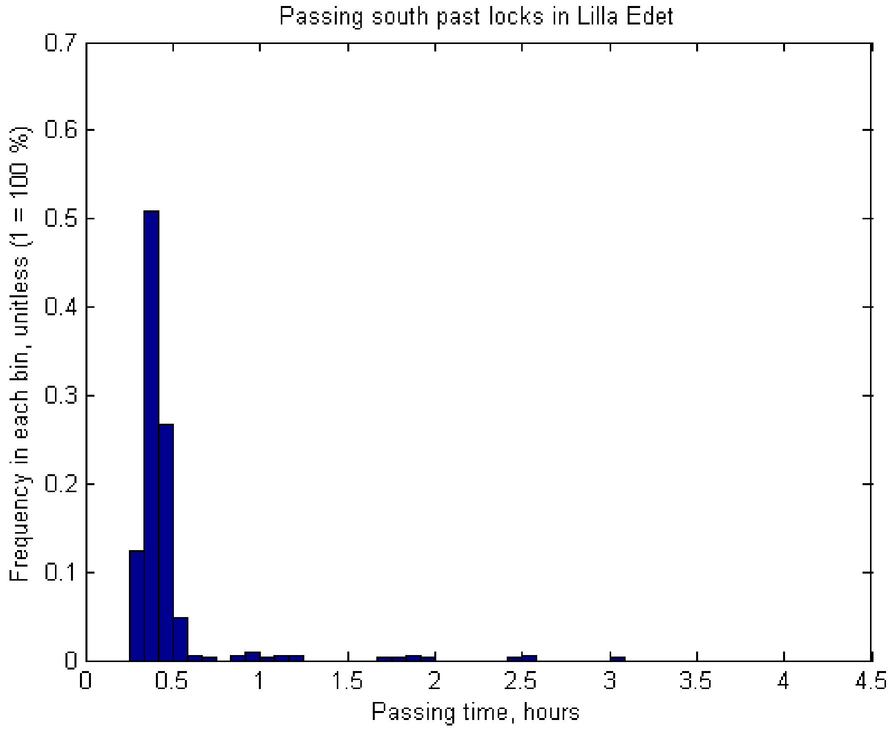


Figure 7: Frequency function of passages through Lilla Edet locks going south, 5 minute time resolution (bins).

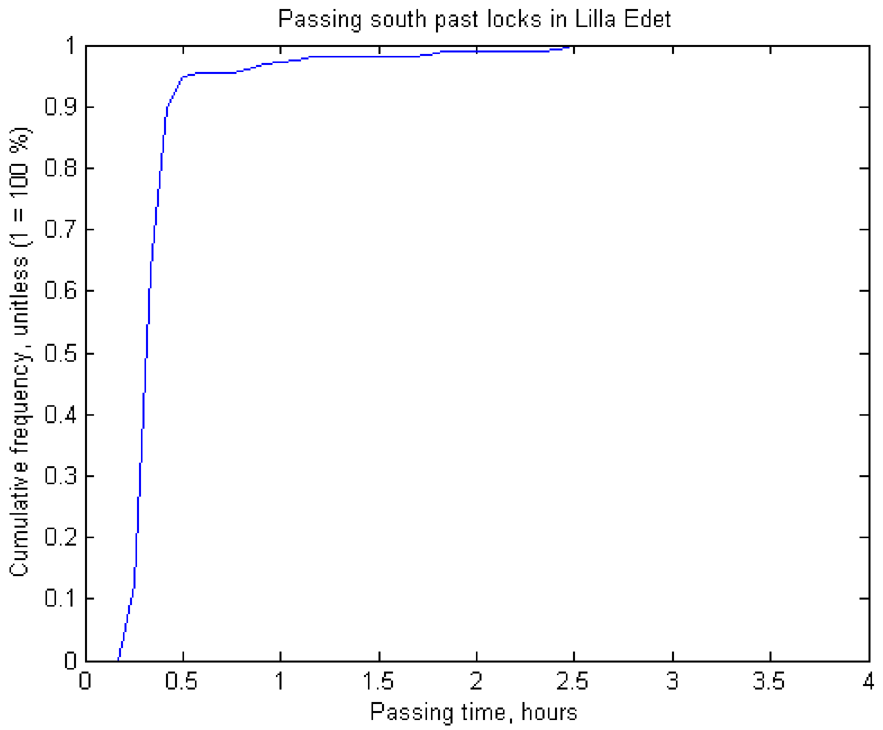


Figure 8: Cumulative distribution of passages through Lilla Edet locks going south, 5 minute time resolution (bins).

1.1.2 AIS data for passage through Trollhättan locks

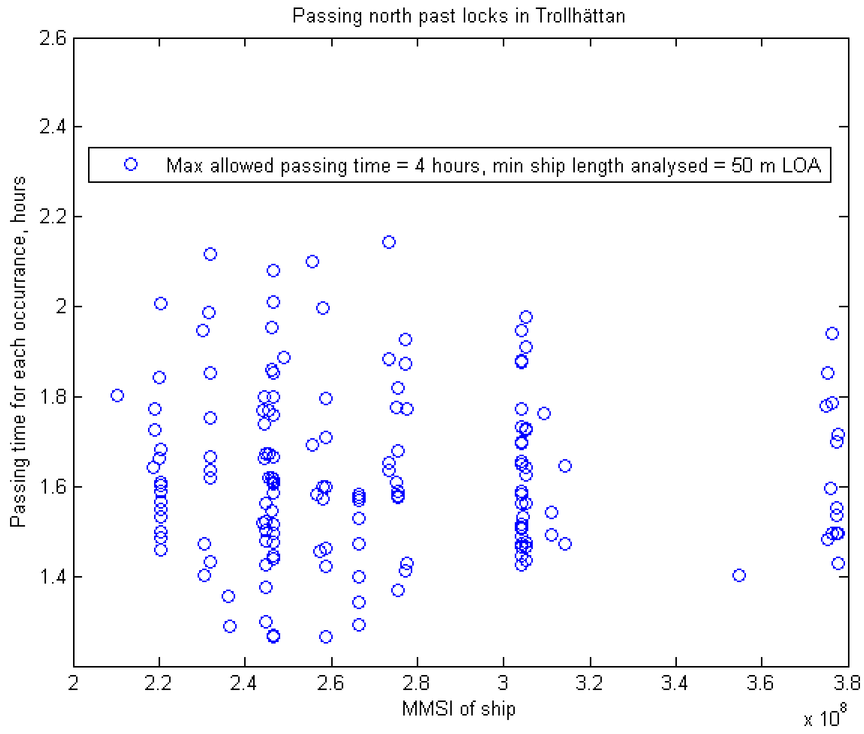


Figure 9: Data of all passages through Trollhättan locks going north (ships with LOA above 50 m)

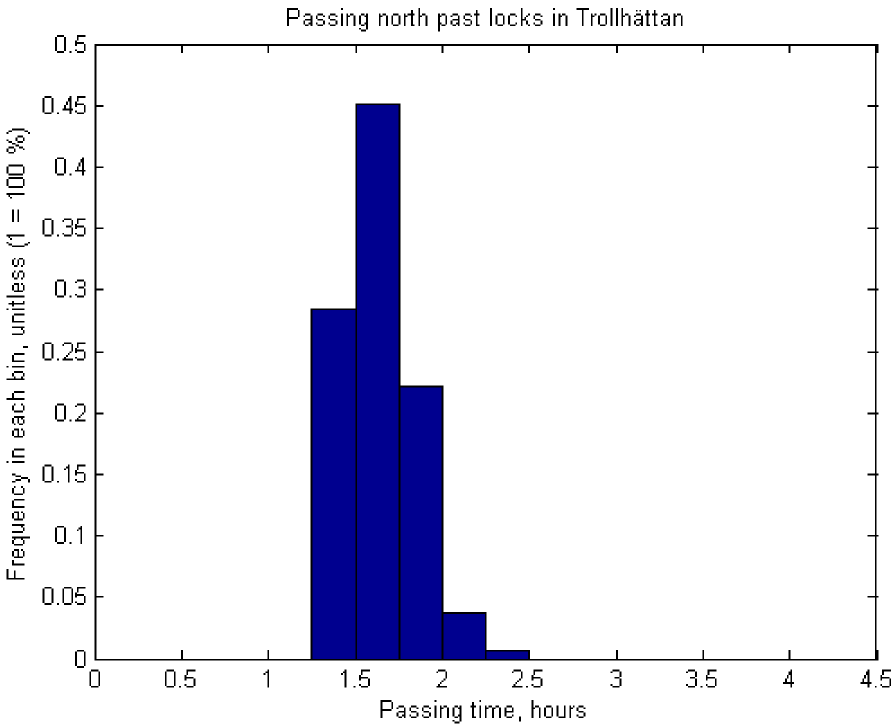


Figure 10: Frequency function of passages through Trollhättan locks going north, 15 minute time resolution (bins).

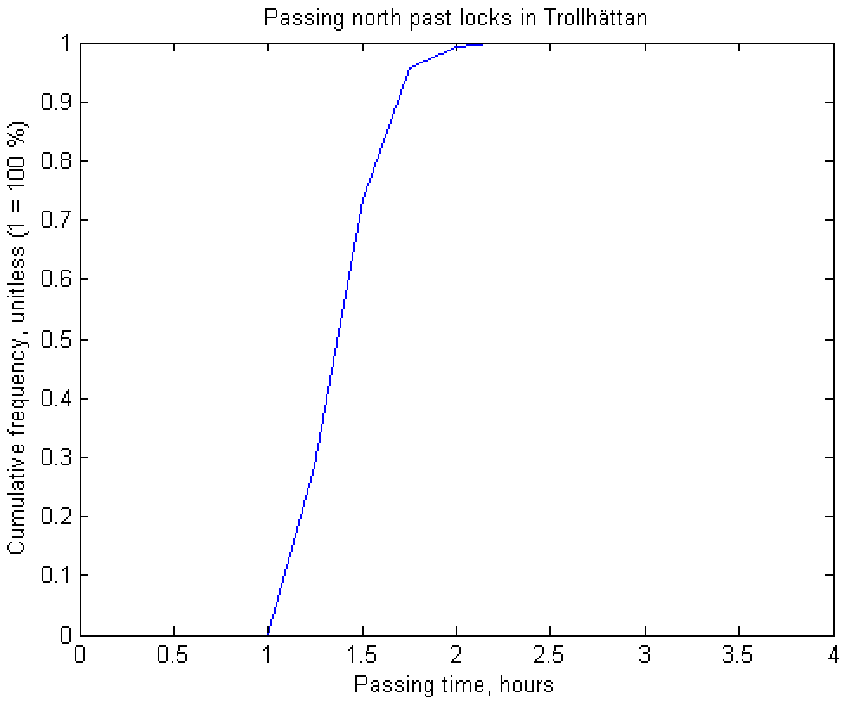


Figure 11: Cumulative distribution of passages through Trollhättan locks going north, 15 minute time resolution (bins).

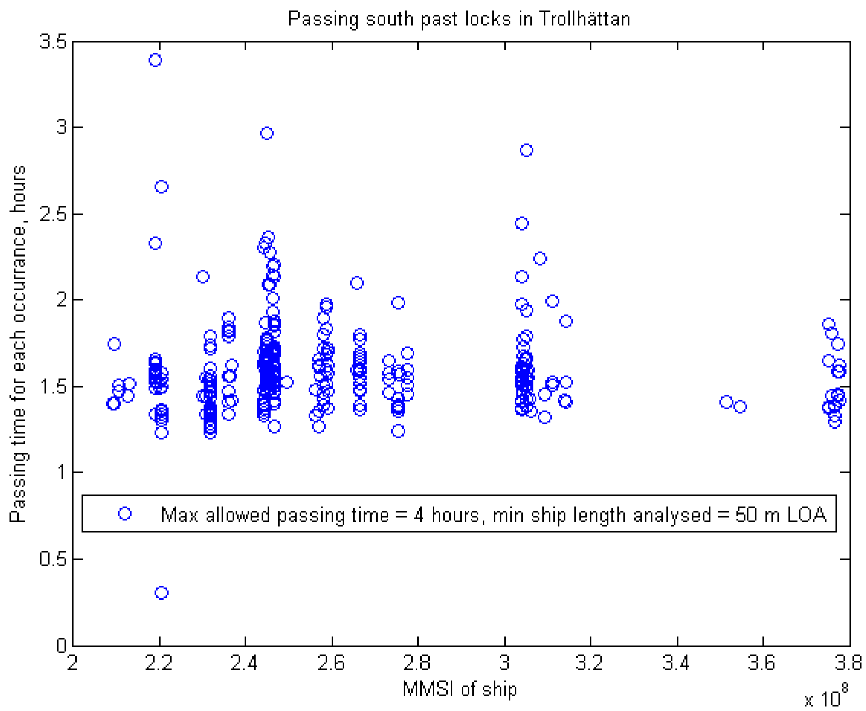


Figure 12: Data of all passages through Trollhättan locks going south (ships with LOA above 50 m)

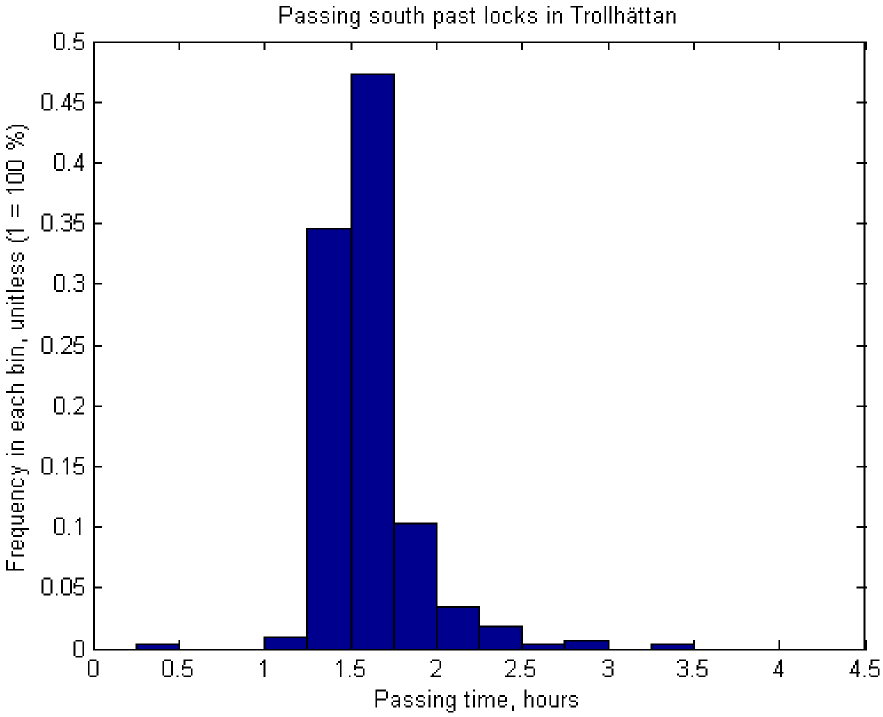


Figure 13: Frequency function of passages through Trollhättan locks going south, 15 minute time resolution (bins).

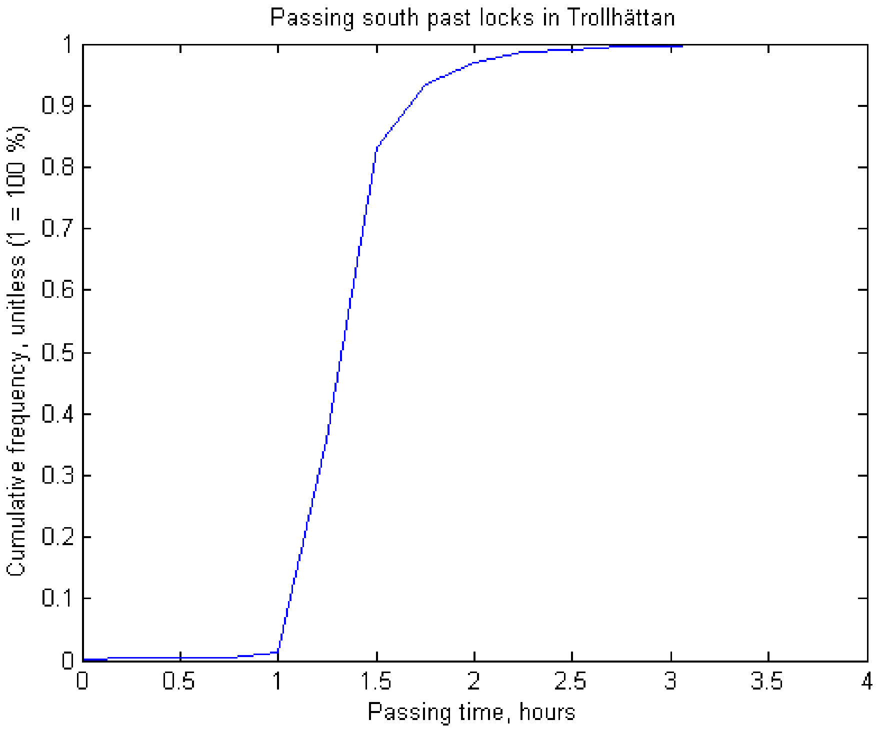


Figure 14: Cumulative distribution of passages through Trollhättan locks going south, 15 minute time resolution (bins).