Sai-MAAX - Final Design Report

Zero emission/multi-navigation/bulk carrier/modernized vessel

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Executive summary

As the fleet of Saimax vessels ages, newbuilds are needed to maintain the attractivity of the Saimaa Canal. The recent proposal to enlarge the locks in the canal has attracted interest in the area and is intended to rejuvenate the marine traffic between Russian and Finnish inlands. The quest for carbon-free shipping poses immense challenges to shipping industry as a whole, but even more so for the vessels operating in the fragile inland ecosystems. No conventional engines can deliver true carbon neutrality, so the team explored more unconventional options.

Given these opportunities, the team designed a truly zero-emission, ice-breaking flexible cargo vessel operating between Lappeenranta and St. Petersburg. Innovations include green hydrogen propulsion and composite materials used in the construction. The main bulk cargo was identified to be timber, with additional consideration given for machinery and containers. The final product was a sound concept combining breakthroughs from various fields on science.

Design team and previous experiences

Figure 1: Sai-MAAX team members.

Viljami Erkkilä: hull modelling, maritime emission policies

Aaron Körkkö: structure design, advanced materials, testing requirements

Johanna Myllymäki: standardization of materials, material requirements

Anna Nikitina: port and cargo handling requirements, policies in Russian

Juho Suortti: accessing the feasibility of the general arrangement, emission reduction technologies

Project schedule

The project was executed over ten weeks matching the course length. The breakdown of the assignment execution is shown in the Figure 2 below.

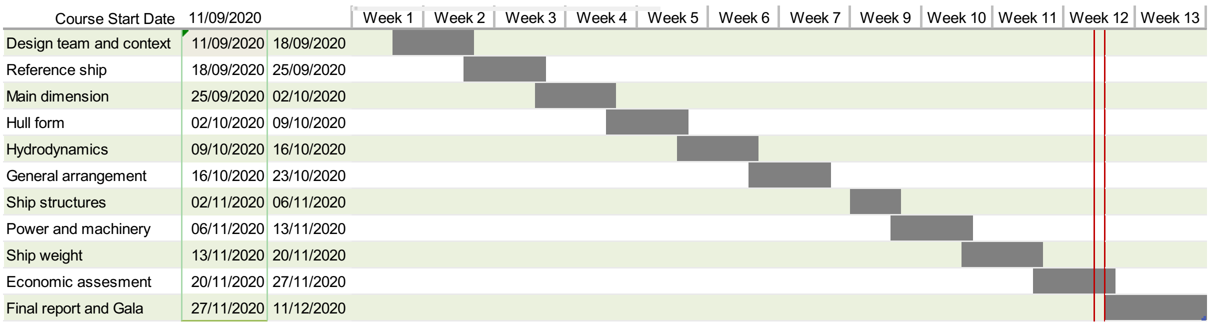

Figure 2: Project Gantt chart.

Team roles

Aaron:	Team Leader/Document Formatting
Juho:	Technical Director/Design Expert/Analysis
Viljami:	Mechanical Drafting/Design Support/Analysis
Anna:	Regulatory and Empirical Methods
Johanna:	Equations and Industry Experience Relations

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Design mission

Description

Our design mission is to create a modernized bulk carrier vessel concept to operate between the ports of Imatra, Finland and St. Petersburg, Russia via the Saimaa Canal. The vessel will be designed so that it incorporates the latest marine technology for the following purposes:

- Ice breaking capability: the vessel will operate in the inland waters of Finland and the Baltic Sea, so it will require provisions to safely and efficiently operate during winter as well as in the summer months.
- Zero-emissions operation: the vessel must use non-traditional forms of fuel or propulsion in order to achieve zero emissions or minimal emissions for the entire service life
- Maximum payload: the vessel must be versatile enough to carry all types of cargo while meeting all regulations and constraints for operation on the specified route. This includes emissions, maximum allowed dimensions for length, breadth, draught, and other construction guidelines

The design will be based on vessels of similar dimensions that currently operate in this region or in other parts of the world and the concept will be tailored to meet emission and ice-capability objectives. The design team will evaluate current advances in technology and incorporate them as necessary and possible.

Description of route of operation

Sai-MAAX is a mixed-navigation vessel because its route begins (or ends) in fresh water of the Saimaa lake region and ends in the Baltic Sea at the port of Saint Petersburg. It is designed to operate in Saimaa canal and inland waterways, and as such, there are emissions, wave generation, speed, and other restrictions that must be taken into account.

An overview of the route is shown in the Figure 3 below and was generated on https://www.vesselfinder.com/ based on the estimate distance feature; the starting point is in Imatra, Finland and the ending port is in Saint Petersburg, Russia which is an estimated 129 nautical miles or approximately 250km for one-way travel between the ports. The operational profile with the suggested speed, mission time and operational areas is presented in the Figure 4.

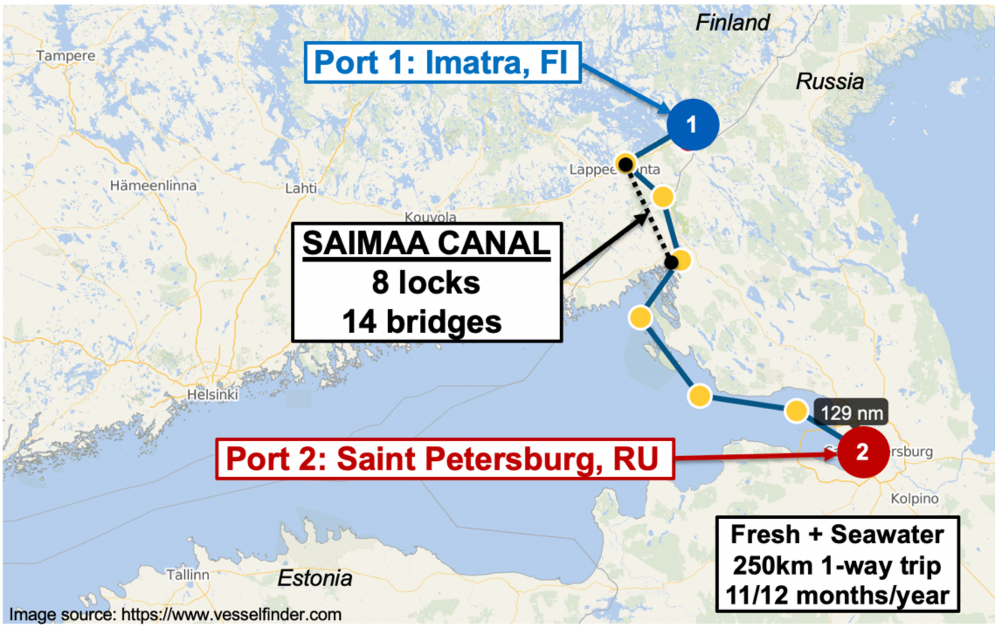


Figure 3: Suggested route outline.

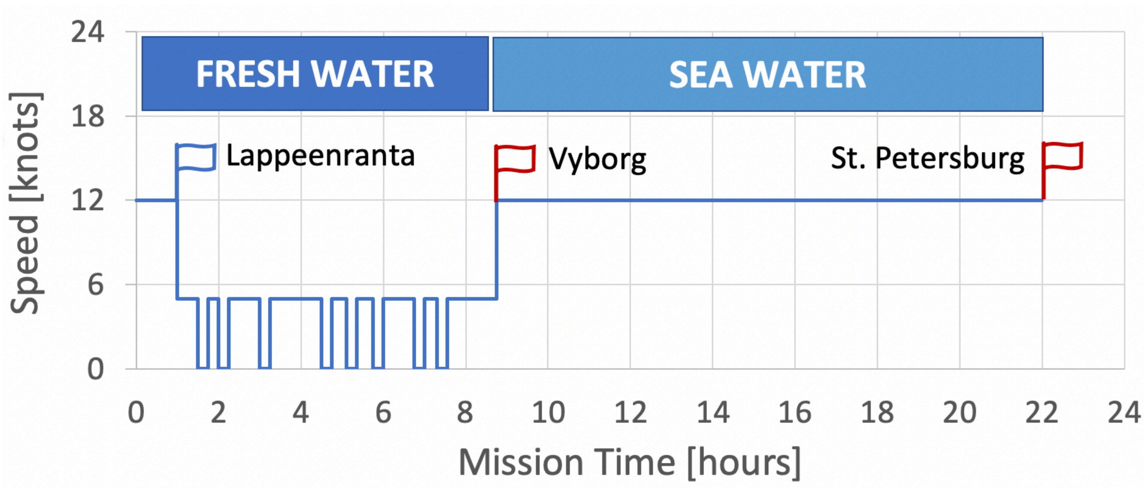


Figure 4: Suggested operational profile.

Design innovations

Fuel cells generate electricity from hydrogen-rich fuels with high efficiency, and when operating on pure hydrogen are truly emission-free. While burning LNG in the cell creates greenhouse gases, LNG could function as an intermediary step whilst pursuing true zero emissions. Fuel cells have typically high capital costs and if burning hydrogen, also high operating costs. Since fuel cells generate electricity, an electric powertrain is a necessity and further increases costs. Storing hydrogen is also problematic: compressed hydrogen is volumetrically very inefficient and expensive, while liquid hydrogen poses its own problems due to safety issues and cryogenic temperatures.

Reducing the weight of the ship reduces fuel consumption and/or increases cargo capacity. Possible material candidates include aluminium alloys and glass/carbon fiber composites, though latter seems unlikely due to the cost. Studies have shown that reducing the weight of the superstructure achieves noticeable savings in lightship weight without sacrificing structural integrity. The operation in frozen waters imposes limitations to the advanced material usage in load-bearing structures, therefore the vessel's hull will be constructed mainly from steel.

As the storage of gaseous fuels is heavily regulated, finding space for large tanks in a volume-limited design may prove difficult. To move the crew out of the harm's way, forward superstructure solution can be utilized.

State-of-the-art battery systems can reach power densities suitable for extended marine operation but come with extremely high capital expenditures. Unlike hydrogen systems, the weakness of batteries is constant high weight instead of wasted space. Modern lithium-ion batteries also have a very limited lifecycle: even the best solutions reach only about 2000 cycles, requiring expensive refurbishment at periodic intervals. (8) However, batteries excel at balancing the peak load and giving auxiliary short-burst power, and in such applications lower capacities are acceptable.

Design challenges

Mixed navigation ships are subject to hull form optimization: on one hand, cubical hull allows for the greatest payload, but on the other, the sleek hull lines reduce resistance. Sai-MAAX design team must recognize factors at play and find a comfortable balance. Northern winter with its ice-conditions also imposes limitations on hull form, demanding less steep bow geometry. River traffic requires restrictions on wave heights: in Russian waters design wave height is limited at 3-4 meters, depending on circumstances. Inland operation also means that any pollutions emitted by the ship are inherently close to residential areas and fragile ecosystems, so besides minimizing GHG emissions, bilge and ballast water discharges must be managed accordingly.

If ships originally designed for open water are operated in draught-limited inland waterways, they might be forced to sail on partial loads and thus suffer from higher hydrodynamic resistance, for example. In worst case they may even require tugboat assistance to navigate through the narrowest passages. An interesting characteristic of Sai-MAAX relates to its payload: with bulk cargo, volume might be a limiting factor but with machinery the weight might be the factor.

Design constraints

Main constraint imposed on the vessel design is the lock dimensions in Saimaa canal. At present, they limit the vessel to 82,5m x 12,6m x 4,35m (length x breadth x draught), but planned upgrades increase the maximum length to 93.1m. Bridges on Russian side might limit air draught of the vessels. The locks of the canal set the limitation of 24,5m. The length of the Saimaa Canal alone is 43,3km from Lauritsala, Lappeenranta, Finland to Vyborg, Russia. (6)

Locks in Volga-Baltic waterways allow larger ships than those of Finland (except that the draught is limited at 4,20 meters) and thus the route could be extended thousands of kilometres into the Russian heartlands, if the need would arise in the future.

When shipping in Finnish inland waterways, there are multiple legislations that must be considered. Low emissions are only one of the various requirements the vessel must meet.

The main Russian legislative body, *Russian Maritime Registry of Shipping*, mandates the ships going through Saimaa Canal to comply with at least M-PR class for summer (3,0m design wave height) and M-SP (3,5m design wave height) for year-round navigation. In general, the Canal is open for navigation up to 11 months a year with median usage time of 211 days a year. The general recommendation for ice class in the region is Ice Class 30 or 40 of the Russian River Register which translates to the maximum ice thickness of 30-40cm. (2, 3)

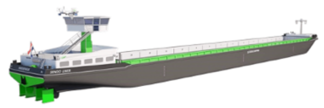
All the cargo ships travelling through the Russian waterways are required to have on board systems for water and exhaust purification, as well as follow requirements for the hull walls thickness if the diesel fuel is transported aboard. (3, 4) Russian legislation does not limit the usage of the fossil fuels and diesel as the main fuel for the inland ships, however it introduces the recommendations for the allowed concentration of harmful substances in exhaust gases. (5)

Design variables

In this project the key functional characteristics are the range, the engine power and the cargo capacity. The total length of the chosen route (Imatra – Saint Petersburg) is about 250 kilometres. The vessel should have a range of about 600km in order to be able to perform a round trip comfortably.

The power requirement of the ship can be estimated using reference vessels already sailing a similar route or having similar key dimensions. Newest vessels listed by Lebedeva et al. suggest that a ship of these dimensions generally has about 2000 kW of engine power at design cruise speed of 12 knots. Due to waiting times in locks, relatively short route and zero-emission characteristics our team decided that 12 knots is appropriate design speed. InFuture project examines the potential of Russo-Finnish inland waterways and estimates that with upgraded locks in Saimaa canal, vessels reach a payload of 3000-3300 tonnes. (7)

Reference ships



L: 110.0m | B: 11.45m | T: 3.75m | DWT: 3400t

Sendo Liner – *Netherlands*

- Inland container vessel
- German and Dutch inlands
- Innovations – batteries, composites

L: 128.2m | B: 16.74m | T: 4.34m | DWT: 5485t

Rusich – *Russia*

- Multi-navigation and multi-cargo vessel
- Russian inlands and Baltic region
- Recently built conventional vessel

L: 82.5m | B: 12.50m | T: 5.35m | DWT: 3500t

Royal Andrea – *Netherlands*

- Multi-navigation bulk cargo vessel
- Saimaa operating region
- Detailed ballast information

Figure 5: Overview of selected reference ships.

Selection methodology

Reference ships, the general overview of which is shown in the Figure 5 above, are chosen based on similarity to the general characteristics and operating requirements that Sai-MAAX intends to fulfill, namely;

1) Inland/mixed navigation vessels typically have a fairly slow design speed of 10-12 knots, and average speeds even lower than that (Fleetmon database lists average speeds around 7 knots for inland vessels). To make use of the empirical data, our ship should also have similar speed characteristics.
2) This type of vessel generally has a very rectangular cross-section, as well as steep bow and stern, meaning high block and midship coefficient (0.8-0.85 and over 0.9, respectively). Inland vessels generally have a long parallel midship and a high breadth to draught ratio due to shallow waters they operate in.
3) Historically, inland vessels operating in vicinity of Baltic sea have had a very long lifespan. Current fleets consist of very old ships, with the most numerous series having an average age of 45 years. (2) Factors that explain this include freshwater environment, lack of wave loads stressing the structure and the absence of international legislation. Sai-MAAX, however, will not enjoy these privileges because of its trip through the Baltic Sea on its way to port in St. Petersburg in Russia.
4) Because of the calm waters, hull friction of inland vessels contributes around 75% of the resistance and wave slamming resistance the last 25%. The wetted portion of the hull area is traditionally very high. The bows of inland vessels are generally very steep for this reason, but Sai-MAAX requires a bit more seaworthy bow design.
5) Ships operating in coasts of Baltic Sea and inland waterways in its immediate vicinity generally do not operate during the winter months, and this is reflected in their hull

form and engine power. Sai-MAAX will thus require higher engine power and ice-breaking bow compared to existing mixed-navigation vessels.

Sendo Liner

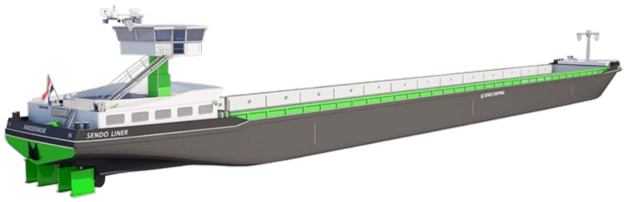


Figure 6: Sendo Liner.

The first reference ship chosen for the Sai-MAAX project is the Sendo Liner from the Netherlands, the general outlook of which is presented in the Figure 6 above. The ship is an inland cargo vessel with deadweight of 3400 tonnes and length x beam x draught is $110\ m$ x $11.45\ m$ x $3.70\ m$. It is powered by two Volvo Penta D16 diesel electric engines as well as battery packs to allow for hybrid operation of the vessel. The top speed is approximately 12 knots. It has several innovations, which made it win the KNVTS Ship of the Year Award 2019. The vessel was designed so that it will be able to be modified in the future to allow for hydrogen fuel cell or LNG conversion. The design criteria of the ship included staying at the top of the low-emission fleet for the entire ship lifetime.

Technical information:

- Inland cargo vessel
- 14 rows of containers instead of usual 13 rows
- Length $110\ m$
- Beam $11.45\ m$
- Draught $3.70\ m$
- DWT 3400 tonnes
- 2x Volvo Penta D16 Genset diesel engines
- Additional power provided by battery pack ($540\ kWh$)

Innovations:

- 40% reduction in CO_2 measured on a per container basis
- Water ballast to decrease air draft for low-clearance bridges in the Netherlands
- Hull design optimized to reduce drag
- Two propellor drive which is unique for inland operation

Required adaptations for Sai-MAAX:

There are several updates that need to be made to tailor this vessel to the requirements of the Sai-MAAX project, first the power must be increased to approximately $1500\ kW$ in order to achieve ice breaking capability in the region of operation. The length of $110\ m$ must be reduced to fit into the Saimaa Canal with planned maximum length of no larger than $93.1\ m$. Currently, this is a low-emission ship, and the design plan is to create a zero-emission concept, so additional details are needed regarding the battery bank increase in size or adding in LNG or hydrogen fuel cells. Overall, this is a very similar ship to what the Sai-MAAX is trying to accomplish and is very recently put into service, so it is fortunate that this exists, and it makes the concept of Sai-MAAX much closer to reality than other innovative solutions.

Rusich

Figure 7: Rusich-2 in icy waters.

The second reference ship chosen is the 00101 project, Rusich type by Maritime Engineering Bureau, Ukraine, depicted in the Figure 7 above. 11 sister ships were built since 2011 in different shipyards around the globe and are mostly sailing in Russian waters, both inland and at sea. The ship has a deadweight of 5485 tonnes in seawater and 3860 tonnes in freshwater. The main dimensions are: length $128.2\,m$, breadth $16.74\,m$ and draft of $4.34\,m$ in seawater and $3.6\,m$ in freshwater. The design speed is $11\,kn$ and the ship is equipped with two Wärtsilä 6L20 diesel engines producing $2280kW$ of propulsion power. This engine is fully compliant with IMO Tier II exhaust regulations; however, this is not enough to fulfil the zero-emission or close to zero-emission target of the project. The ship of this design complies with the ice class regulations needed for navigating in Saimaa Canal, and allows for relatively high deadweight compared to the size. The ship does not carry a lot of innovations, but it has suitable draft and close breadth, and the data about this ship is found in abundance from different sources.

Rusich-type ships are generally used for transporting bulk materials such as ore, fertilizers, ammonium nitrate, grain, coal; metal in pipes and sheets; ISO 20’ and 40’ containers and wood.

Required adaptations for Sai-MAAX:
Despite lacking innovations in its design, the ship has a required ice class and proved its ice going capabilities during the years of service. However, its shape has to be resized to fit the Saimaa Canal locks: the length must be reduced to $93.1\,m$ and the breadth to $12.6\,m$. Secondly, the engine type should be rethought, as at the moment diesel engine even using biofuel will not meet the zero- or close-to-zero-emission requirement set as the design goal. The general arrangement picture of this ship is available online, but its structure should be improved to increase the allowed deadweight. The scalability of the ship design is a controversial topic, but with this reference ship an idea about ice-going requirements can be obtained.

The Table 1 below shows the key properties of the vessels. The Froude’s number in Table 2 describes the ship’s hydrodynamic performance, whereas block coefficient tells us about its shape.

Table 1: Key properties of reference ships and Sai-MAAX.

	Length(m)	Breadth (m)	Draught (m)	Power (kW)	Speed (kn)	DWT (t)	Displacement(t)
Sendo	110	11.45	3.70	870	(8-10)	3400	
Rusich	128.2	16.74	4.34	2280	11	5485	8032
DCV36 Amethyst	89.95	14.5	6.4	2640	12	5026	7034
Sai-MAAX	93.1	12.6	4.45	~1500	12	maximize	

Block coefficient (C_B) is the ratio of the volume of displacement to the product of the length, breadth, and draught of the ship.

Table 2: Performance indicators of reference vessels and Sai-MAAX.

	Froude's Number	Block coefficient
Sendo	-	-
Rusich	0.1596	0.8624
DCV36	0.207	0.8427
Sai-MAAX	0.204	~0.8

Royal Wagenborg – Andrea

Figure 8: Royal Wagenborg Andrea in operation.

Reference ship Andrea (Royal Wagenborg), seen in the Figure 8, was chosen as an additional reference vessel It was chosen because of the operating region, type of cargo, position of the superstructure and bridge, recent construction, and details regarding the ballast system, which were lacking for other reference ships. Andrea has DWT of 3500 tonnes and water ballast of $1710\ m^3$ which represents 49% of the total DWT. As seen in the Table 3 Sai-MAAX is smaller than the Andrea, however $1000\ m^3$ should be sufficient ballast for operation. Ballast tanks in the double bottom will hold approximately $760\ m^3$ and the remainder is located mostly to aft end of the vessel, with the fore peak tank located within the collision bulkhead.

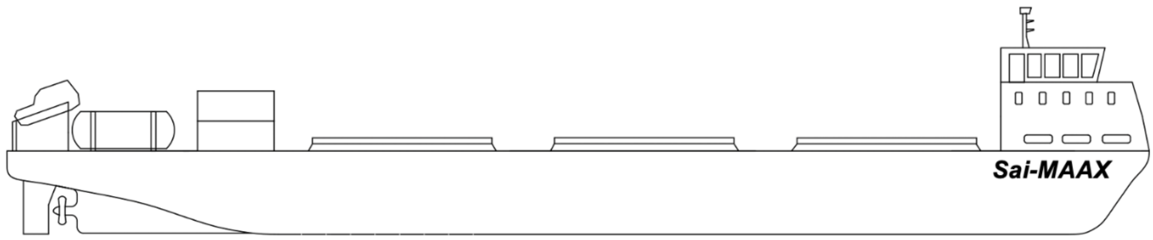
Table 3: Royal Wagenbord Andrea and Sai-MAAX main parameters comparison.

Parameter	Andrea	Sai-MAAX	Unit
LOA	82.5	93	m
DWT	3500	2570	tonne
B	12.5	12.6	m
T	5.35	4.45	m
D	8	6.8	m

Dimensions & hull

Main dimensions

Based on the constraints and requirements discussed previously and further in the report, the preliminary design with the general outlook and parameters summarized in the Figure 9 below was created. The main dimensions and speed requirements were discussed at great length in the previous parts of the report.



Main Dimensions	
Length*	93.10 [m]
Breadth*	12.60 [m]
Draft*	4.45 [m]
DWT	**2570 [t]**
Depth	6.80 [m]

*Maximum allowed by Saimaa Canal planned dimensions

Speed and Cargo	
Top speed	**12.0 [kts]**
Ship type	Multi-cargo
Bulkheads**	8
Cargo holds	3
Capacity	**3000 [m³]**

**Six stationary bulkheads and two movable

Coefficients	
Froude No.	0.210
C_B	**0.742**
C_M	0.995
C_P	0.765
C_W	0.750

Figure 9: Side view of Sai-MAAX and overview of main dimensions.

Hull form

The lines plans of the body (Figure 10), as well as profile and half-breadth (Figure 11) are presented below. The figures in this report were created using DELFTship software, however they were verified using the spreadsheet provided by the course instructor. The green lines in the Figure 10 indicate the stations, while the orange lines of Figure 11 represent buttocks and blue – waterlines. The outer edges of the ship are marked black.

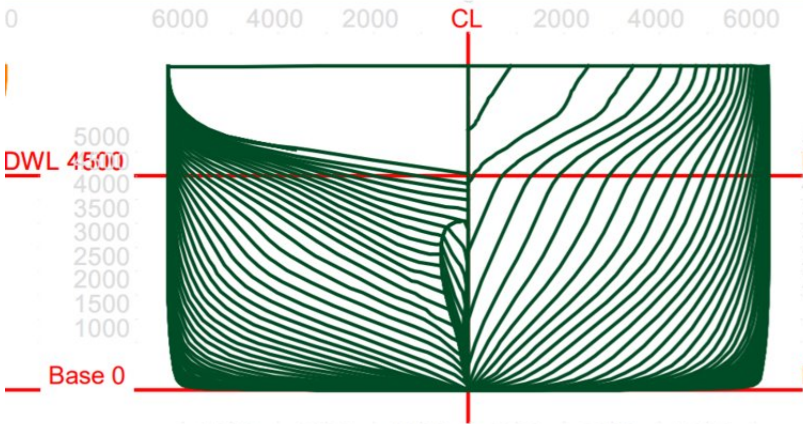


Figure 10: Body plan.

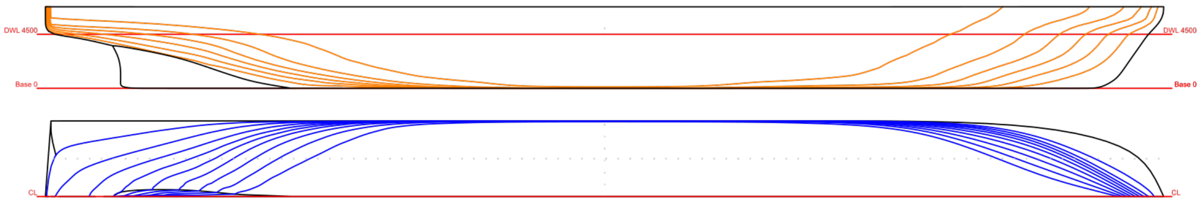


Figure 11: Profile and half-breadth plans.

The figures show that in general, the shape of the hull is quite similar to an average bulk cargo vessel with the rise of the bow is slightly steeper than usual to increase the block coefficient to meet the recommended values while meeting the ice-breaking requirements.

Hydrostatics

Simpson's rule was used to calculate surface areas in underwater waterplane areas and sectional areas. For both number of equally spaced ordinates is 11, and Simpson's first rule was applied, the general formula for which is presented below:

$$A = \frac{h}{3}(y_0 + 4y_1 + 2y_2 + 4y_3 + 2y_4 + \ldots + 4y_{n+1} + y_n)$$

First integrations of sectional areas were performed. Values for waterlines 10, 8, 6, 4, 2, 1 and 0 were found during the lines drawing creation, and offset values for waterline 9, 7, 5 and 3 were evaluated by visually fitting them to the section lines. Since waterlines and section lines are symmetric about the centreline, the ½ ordinates from dimensional offset table could be used to multiply the sum with two to get the total surface area.

The moment of area is also calculated for each waterline and summed for whole sectional area. The centre of area can then be extracted by applying the formula below:

$$\text{Centre of area} = h \cdot \frac{\Sigma MA}{\Sigma V}$$

To simplify the calculations, the spreadsheet provided by the course instructor was used. An example of calculations of cross-sectional area at section line 3 is shown in the Figure 12, and the resulting section line and the centre of cross-sectional area are in the Figure 13.

Maximum draft	4,45	m
Intervals:	10	-
Spacing, s:	0,445	m

WL [-]	Z-coordinate	1/2 ordinates y_n [m]	SM k_n [-]	Product for area $y_n \cdot k_n$ [m^2]	Lever @ Frame 0 R_n [m]	moment of area $y_n \cdot k_n \cdot R_n$ [m^3]	
0	0	4,914	1	4,9	0	0,0	
1	0,445	5,796	4	23,2	1	23,2	
2	0,89	6,111	2	12,2	2	24,4	
3	1,335	6,245	4	25,0	3	74,9	
4	1,78	6,300	2	12,6	4	50,4	
5	2,225	6,300	4	25,2	5	126,0	
6	2,67	6,300	2	12,6	6	75,6	
7	3,115	6,300	4	25,2	7	176,4	
8	3,56	6,300	2	12,6	8	100,8	
9	4,005	6,300	4	25,2	9	226,8	
10	4,45	6,300	1	6,3	10	63,0	
			Σ	185,0	m^2	941,6	m^3

Cross sectional area	54,9	m2	
Center of CSA	2,265	m	above keel

Figure 12: Cross-sectional area calculations at section line 3.

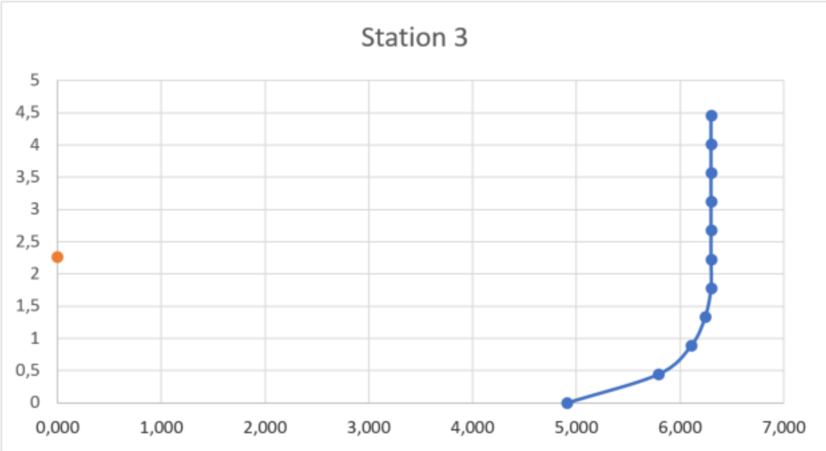


Figure 13: Section line and center of area for CSA 3.

Same method was applied for waterplane areas. Same fitted values for waterlines 9, 7, 5 and 3 were used as for sectional lines. The example for waterline 10 is shown in the Figure 14 below, and it includes the outline of waterline and location of L_{CF}.

Length	89.1	m
Intervals:	10	-
Spacing, s:	8.91	m

Input	
Calculation	:::

Frame	x-coordinate	1/2 ordinates	SM	Product for area	Lever @ Frame 0	moment of area	
		y_n	k_n	$y_n * k_n$	R_n	$y_n * k_n * R_n$	
[-]		[m]	[-]	[m²]	[m]	[m³]	
0	0	1.575	1	1.6	0	0.0	
1	8.91	4.410	4	17.6	1	17.6	
2	17.82	6.174	2	12.3	2	24.7	
3	26.73	6.300	4	25.2	3	75.6	
4	35.64	6.300	2	12.6	4	50.4	
5	44.55	6.300	4	25.2	5	126.0	
6	53.46	6.300	2	12.6	6	75.6	
7	62.37	6.300	4	25.2	7	176.4	
8	71.28	6.237	2	12.5	8	99.8	
9	80.19	5.292	4	21.2	9	190.5	
10	89.1	0.000	1	0.0	10	0.0	
			Σ	166	m²	837	m³

WPA	986	m2
LCF From fr0	44.905	m

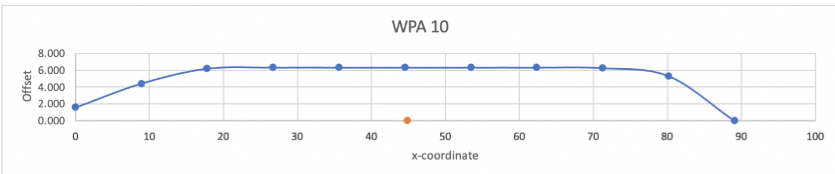


Figure 14: Waterplane area calculations, the resulting waterline and L_{CF}.

In the next phase, the Simpson's first rule was applied to integrate the ship's volume of displacement. First, product for volume was defined with help of cross-sectional areas 0-10. Longitudinal centre of buoyancy (L_{CB}) was also calculated based on the formula below, and the calculations are summarised in the Figure 15.

$$L_{CB} = h \cdot \frac{\Sigma MA}{\Sigma V}$$

Length	89.1	m
Intervals:	10	-
Spacing, s:	8.91	m

Input
Calculation

Frame [-]	x-coordinate	Cross-sectional area A_n [m²]	SM k_n [-]	Product for volume $A_n * k_n$ [m³]	Lever @ Frame 0 R_n [m]	moment of volume $A_n * k_n * R_n$ [m⁴]	
0	0	1	1	1	0	0	
1	8.91	9	4	37	1	37	
2	17.82	40	2	80	2	160	
3	26.73	55	4	220	3	659	
4	35.64	56	2	111	4	445	
5	44.55	56	4	222	5	1112	
6	53.46	55	2	111	6	665	
7	62.37	55	4	222	7	1551	
8	71.28	52	2	104	8	830	
9	80.19	28	4	112	9	1012	
10	89.1	0	1	0	10	0	
		0	Σ	1220	m³	6471	m⁴

Volume	3623	m3
Density of water	1.025	t/m3
Displacement	3713.07	t
LCB from fr0	47.273	m

Figure 15: Displacement and L_{CB} calculated by cross-sectional areas.

Same template could be used for volume by waterplane areas, as seen in the Figure 16. In this case, vertical centre of buoyancy above the keel (K_B) is calculated with the help of first moment of volume. The result was 2.393 meters above the keel, while Hull lines spreadsheet gave a value of $2.34\ m$.

Maximum draft	4.45	m
Intervals:	10	-
Spacing, s:	0.445	m

Input
Calculation

WL [-]	Z-coordinate	WPA y_n [m²]	SM k_n [-]	Product for volume $y_n * k_n$ [m³]	Lever @ keel R_n [m]	moment of volume $y_n * k_n * R_n$ [m⁴]	
0	0	557.0	1	557.0	0	0.0	
1	0.445	657.0	4	2628.0	1	2628.0	
2	0.89	720.0	2	1440.0	2	2880.0	
3	1.335	762.0	4	3048.0	3	9144.0	
4	1.78	797.0	2	1594.0	4	6376.0	
5	2.225	820.0	4	3280.0	5	16400.0	
6	2.67	838.0	2	1676.0	6	10056.0	
7	3.115	886.0	4	3544.0	7	24808.0	
8	3.56	927.0	2	1854.0	8	14832.0	
9	4.005	956.0	4	3824.0	9	34416.0	
10	4.45	986.0	1	986.0	10	9860.0	
			Σ	24431.0	m³	131400.0	m⁴

Volume	3623.9	m3	
KB	2.393	m	above keel

Figure 16: Volume of displacement and K_B calculated by waterplane areas.

Both methods gave pretty much exactly the same volume of $3623\ m^3$, as seen from the bottom part of the Figure 15 and Figure 16. For the reference, the aforementioned hull lines spreadsheet gave a displacement of $3708\ m^3$.

Results of these calculations seem valid. The percentage form of LCB was calculated using the following formula:

$$\frac{L_{CB} - L_{PP}/2}{L_{pp}} \cdot 100$$

resulting in value about $+2{,}9\%$ forwards from amidships. This is right at the Benford's boundary and may warrant extra fullness to stern area.

General arrangement

Special considerations

Sai-MAAX is intended to be a modernized and future-proof cargo vessel to service the ports between Imatra, Finland and St. Petersburg, Russia. As such, the main objectives are shown in the Figure 17 below as well as the mission statement of this project; ice class, zero emissions, and maximized payload are the primary focuses but other objectives were considered as well such as aesthetics and multi-functional use of space.

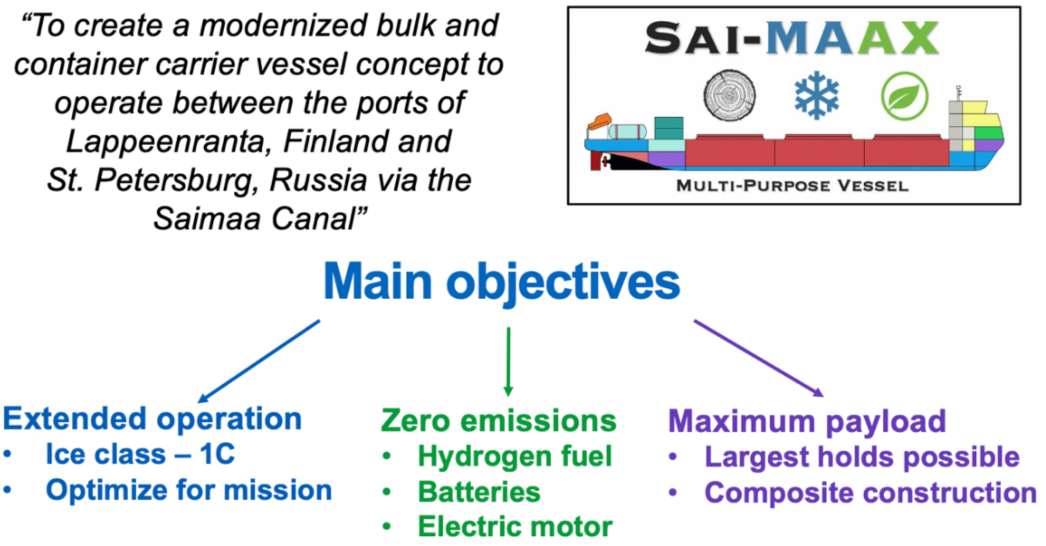


Figure 17: Sai-MAAX mission and main objectives.

General arrangement of Sai-MAAX

The general arrangement from side view is shown in the Figure 18 below. We can see that the majority of the volume is for cargo holds which is one of the main objectives of this project. The other areas follow naturally from basic naval architecture concepts and based on the team's analysis meet the requirements for operating in the Saimaa and Baltic region. Further refinement of the general arrangement is recommended in subsequent design cycles because the fidelity of this arrangement is low but can be improved with increased focus on the specific layout of the components.

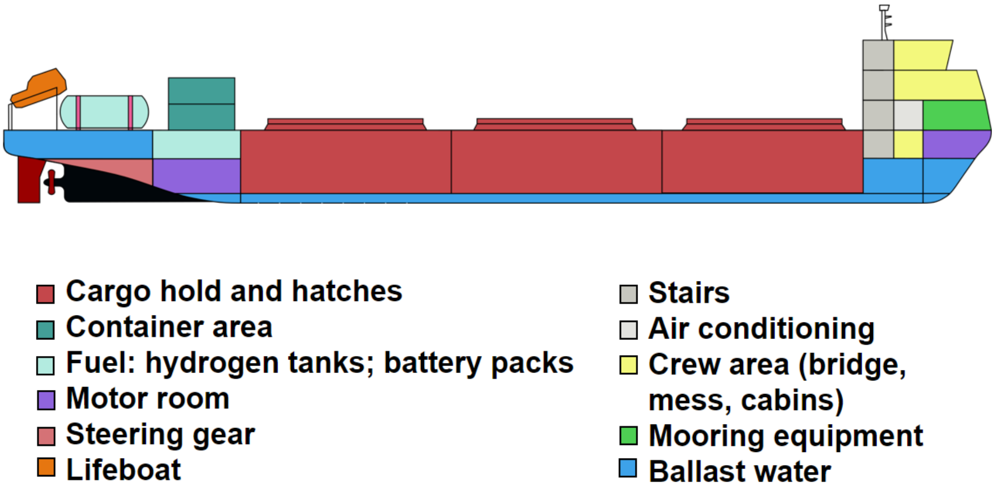


Figure 18: Side view of Sai-MAAX general arrangement.

The deck drawings in the figures 19-22 were drafted according to requirements from cargo volume and other design rules for number of bulkheads, height of double bottom calculations from *DNV GL Rules for Classification guide published in July 2020.* However, it is worth noting that these are preliminary drawings and they need to be refined during more detailed design stage. The deck heights are as follows:

- Double bottom: $1000\ mm$
- Intermediary deck: $4000\ mm$
- Main deck: $6800\ mm$
- Deck 1: $9600\ mm$
- Bridge: $12400\ mm$

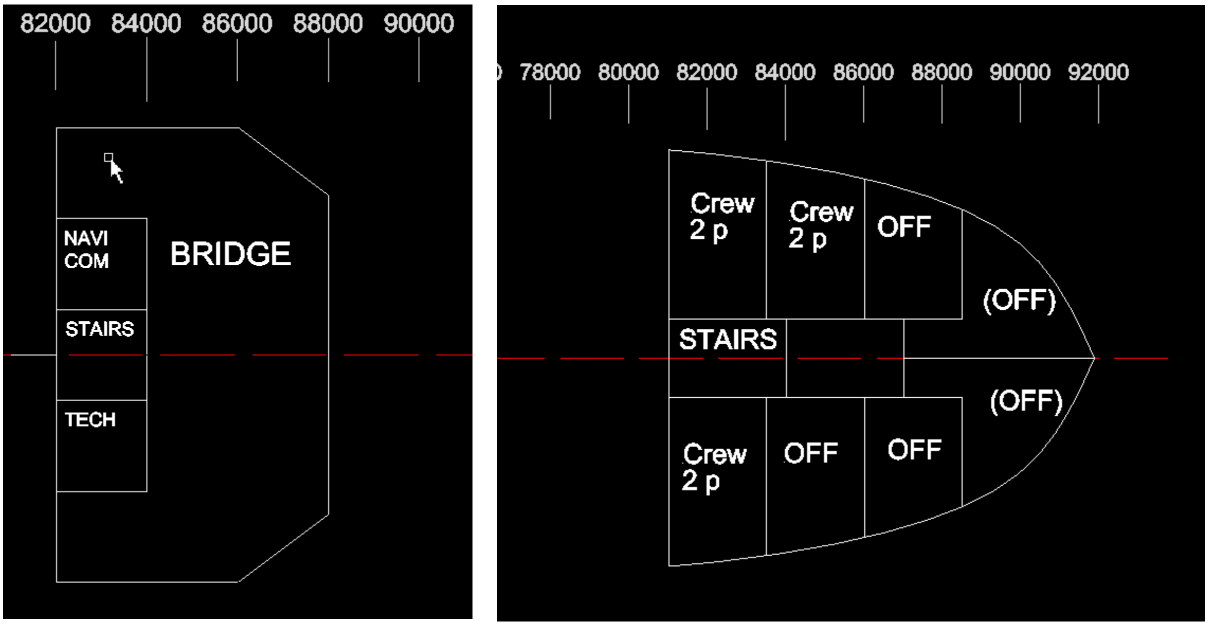


Figure 19: Bridge and deck 1 designs.

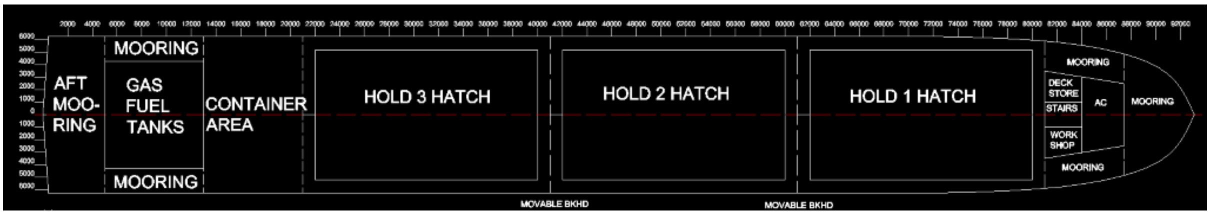


Figure 20: Main deck design.

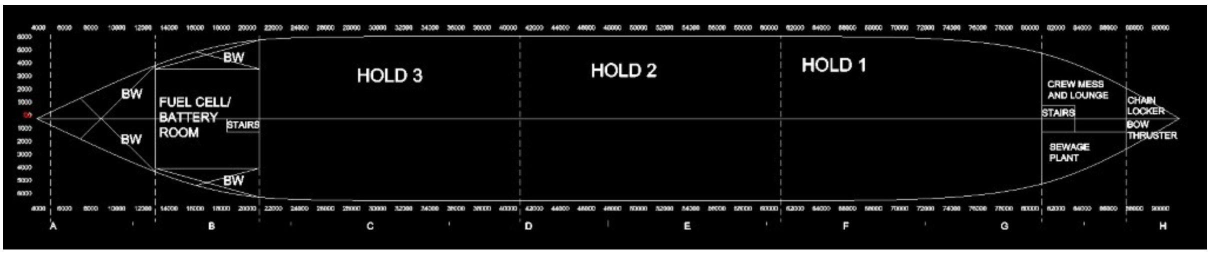


Figure 21: Intermediary deck design.

Figure 22: Double bottom design.

Structural details

Statutory requirements

The following calculations of the force and bending moment requirements come from the DNV-GL Guidelines for Ship Classification. The specific sections of the guidelines are noted in each calculation.

The greatest stresses of hull girder are at the keel and main deck. Longitudinal stresses due to bending moments are effectively capped by yield strength and the shear strength of the material used:

$$\tau_{hg-perm} = \frac{120}{k}, \quad \sigma_{hg-perm} = \frac{205}{k},$$

where k denotes the material factor. The following Table 4 is provided for steels by DNV-GL:

Table 4: Yield strength and material factor k as defined by DNV-GL.

Specific minimum yield strength (MPa)	k
235	1,00
315	0,78
355	0,72
390	0,66
460	0,62

Steels with yield strength exceeding 460 MPa are practically only used in very large container ships, which is not the case of Sai-MAAX.

Minimum midship section modulus

Minimum midship section modulus was calculated from the formula provided by DNV-GL and the calculation is presented below:

$$Z_{R-gr} = k \cdot \frac{1+f_r}{2} \cdot C_W \cdot L^2 \cdot B \cdot (C_b + 0.7) \cdot 10^{-6}$$
$$= 1 \cdot \frac{1+1}{2} \cdot 7.77395 \cdot 93.1^2 \cdot 12.6 \cdot (0.742 + 0.7) \cdot 10^{-6} = 1.18152 m^3$$

where f_r is reduction factor (*which was set as 1*), C_W is a dimensionless wave coefficient equal to 7.77395, and other parameters are known from the ship's main dimensions.

Moment of inertia for midship section

Moment of inertia for midship section was calculated from the formula provided by DNV-GL and the calculation is presented below:

$$I_{yR-gr} = 3 f_r \cdot C_W \cdot L^3 \cdot B \cdot (C_B + 0.7) \cdot 10^{-8} = 3 \cdot 1 \cdot 7.77395 \cdot 93.1^3 \cdot 12.6 \cdot (0.742 + 0.7) \cdot 10^{-8}$$
$$= 3.41938 m^4$$

Stillwater bending moments

Hogging conditions:

$$M_{sw-h-\min} = f_{sw}\big(171C_w L^2 B\big(C_B + 0.7\big)10^{-3} - M_{wv-h-mid}\big)$$

Sagging conditions:

$$M_{sw-s-\min} = -0.85f_{sw}\big(171C_w L^2 B\big(C_B + 0.7\big)10^{-3} + M_{wv-s-mid}\big)$$

where:

$M_{wv\text{-}h\text{-}mid}$ = vertical wave bending moment for strength assessment amidships in hogging condition, as defined in [3.1.1] using f_p and f_m equal to 1.0

$M_{wv\text{-}s\text{-}mid}$ = vertical wave bending moment for strength assessment amidships in sagging condition, as defined in [3.1.1] using f_p and f_m equal to 1.0

Hogging condition:

$$M_{wv-h} = 0.19f_{n\ell-vh}f_m f_p C_w L^2 B C_B$$

Sagging condition:

$$M_{wv-s} = -0.19f_{n\ell-vs}f_m f_p C_w L^2 B C_B$$

where

$f_{nl-vh}, f_{sw} = 1$ and $f_{nl-vh} = 0.58\left(\frac{C_B+0.7}{C_B}\right)$

Hogging: $209930\ kNm$

Sagging: $-0.85 \cdot 209930 = -178440\ kNm$

Dynamic wave bending moments

Vertical: Load case factor multiplied wave bending moments calculated earlier.

Horizontal: $2306\ kNm$, which is

$$M_{wh} = f_p\left(0.31 + \frac{L}{2800}\right) \cdot f_m \cdot C_W \cdot L^2 \cdot T_{LC} \cdot C_B$$

where $f_p, f_m = 1$ and T_{LC} is the design draught.

Maximum permissible shear stress is also related to the yield shear strength of the material (in N/mm^2):

Hull girder ultimate strength

The vertical hull girder ultimate bending capacity at any hull transverse section should follow the criteria:

$$M \leq \frac{M_U}{\gamma_R}$$

where M is vertical girder bending moment in hogging and sagging:

$$M = \gamma_S M_{SW_U} + \gamma_W M_{W\nu}$$

DNV-GL does not apply hull girder ultimate strength check for ships $L < 150\ m$.

Structural continuity

The aft, front and side bulkheads must be effectively supported by underdeck structures. Sides and main longitudinal and transverse bulkheads shall be in line in the various tiers of deckhouse. At the end of superstructure the side plating shall extend beyond the ends of the superstructure.

The effect of structural discontinuities shall be minimized by framing all openings. Large openings are fitted with horizontal stiffeners or continuous coamings or girders.

Being primarily a bulk cargo vessel, Sai-MAAX will have large cargo holds without longitudinal bulkheads. Additionally, movable bulkheads can leave large spans between transverse steel structures. Ensuring adequate support for on-ship cargo cranes is difficult as relying solely to bulkheads is not possible. That being said, one solution is to simply make the crane mounting area move with the non-fixed cargo hold bulkheads.

The ice-breaking capability imposes more strict strength requirements in bow area. In practice, these manifest as thicker shell plate and denser framing. The use of high-strength steel is also limited, since with very thin HS steel plates the hull would require excessive amounts of support members.

Scantling plan

- Tank top and bottom: $1000\ mm$ height, $12\ mm$ and $12\ mm$
- Side shell (single skin): $16\ mm$ plated thickness
- Main deck: $6800\ mm$ from tank bottom, $16\ mm$ plate thickness, $8000\ mm$ hole width
- Longitudinal girders along the deck: 4 each side, $1000\ mm$ height, $16\ mm$ thickness
- Stiffeners in deck underside: 7 each side, $400\ mm$ height, 16 thickness
- Floors in double bottom: 5 pcs, $1000\ mm$ height, $16\ mm$ thickness

With these scantlings, the values presented in Table 5 were obtained from the spreadsheet, where I represents area moments of inertia and Z section moduli, with minimum values extracted from DNV GL guidelines. Lowercase s signifies stresses on decks.

Table 5: Structural parameters of Sai-MAAX.

Elements, $I_{s,tot}$	15.91

I_{BL}	16.56
I (min 3.42)	7.32
Z_{deck} (min 1.18)	2.05
Z_{bottom} (min 1.18)	2.26
s_{deck}	105.99
s_{bottom}	94.17

All the key parameters meet the requirements, albeit deck stresses are on the higher side.

Frame spacing is $\mathbf{800}\ \boldsymbol{mm}$ to ensure even split in midship sections, engine room and accomodation spaces. From the stern the FR3 will be a web frame, and from the first bulkhead (FR6) onwards every 5th frame shall be a web frame.

Machinery & Outfitting

Power

Sai-MAAX will be powered by a hybrid solution of diatomic hydrogen and battery power. These fuel sources will be fed to a transformer which will in turn power the electric motor, hotel loads, and other required loads such as ice load. These loads are calculated below;

For ice class considerations the following formulas are used to estimate Sai-MAAX needs; the calculated value falls below the minimum recommended value so we assume 1000kW minimum.

$$P = K_e \frac{(R_{CH} / 1000)^{3/2}}{D_P} [\mathrm{kW}];$$

Sai-MAAX was initially supposed to have an ice class according to Russian Registry of Shipping, but after reviewing later reference ships the team changed the ice class to Finnish-Swedish 1C. This ice class allows independent operation in consolidated ice of $60\ cm$ thickness. For this calculation, a fixed pitch propeller with diameter $2.5\ m$ was selected, leading to K_e of 2.26. Total resistance was calculated to be $79762\ N$.

Required propulsion power is thus:

$$P = 2.26 \cdot \left(\frac{79762}{1000}\right)^{\frac{3}{2}} \cdot \frac{1}{2.5} = 643kW$$

This is below the DNV GL propulsion power requirements for ice class 1C, which is $1000kW$.

Total resistance for Sai-MAAX is estimated to be $106\ kN$ at 12 knots based on the given spreadsheet. We found a reference that estimated that the wind resistance can be up to 10% of the total resistance [3]. However, our ship has a rather low profile and it only sails in the Baltic sea area, which is not too windy. After reviewing relevant articles, wind resistance was estimated to be about 5% of the total hydrodynamic resistance. The Figure 23 below is the resistance chart without the wind resistance.

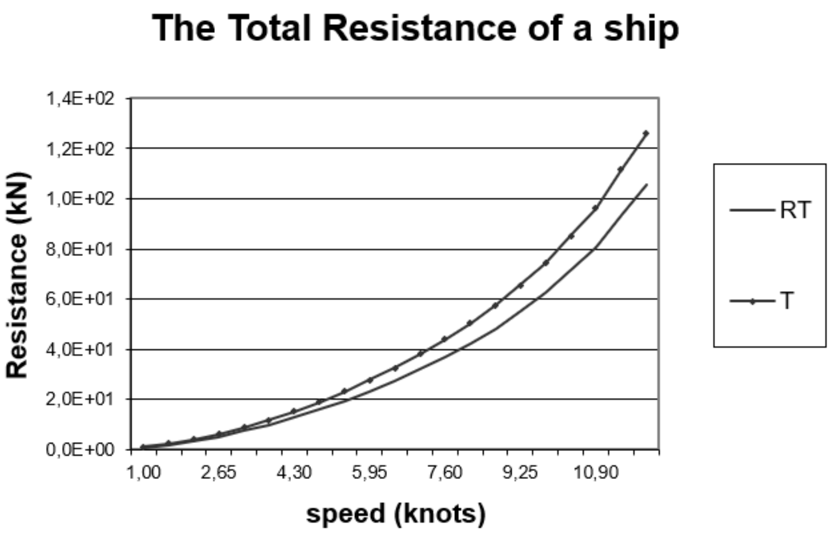


Figure 23: Total resistance of a ship as a function of speed.

Based on the resistance, the propulsion power requirement was estimated to be $880\ kW$ without the wind resistance. Multiplying $880\ kW$ by the wind resistance percentage of 1.05 gives us a total propulsion power requirement of $930\ kW$. As Sai-MAAX has a compact superstructure made from well-insulating composites, a hotel load of $100\ kW$ is estimated. Other auxiliary equipment consumes about $50\ kW$, with the exception of cargo cranes, but these should be fed with shore power. The total power consumption is thus $\mathbf{1080\ kW.}$ Reserve power must be allocated for navigating in thick ice fields and maybe offsetting lock delays by increasing speed. Total power installed onboard, including auxiliary battery packs, is $\mathbf{1500\ kW.}$

Auxiliary power is responsible for all the ship functions other than propulsion and must be available even when main engines are cut off. As our main power generation method produce electricity directly, the main function of auxiliary power generation is to provide redundancy. Typically, auxiliary engines have a power output of about 20% of main engine's power [4]. To ensure secondary supply of power in case of e.g., hydrogen containment breach, about $100\ kW$ of batteries should be installed. These batteries will be distributed both to the bridge and to the engine room.

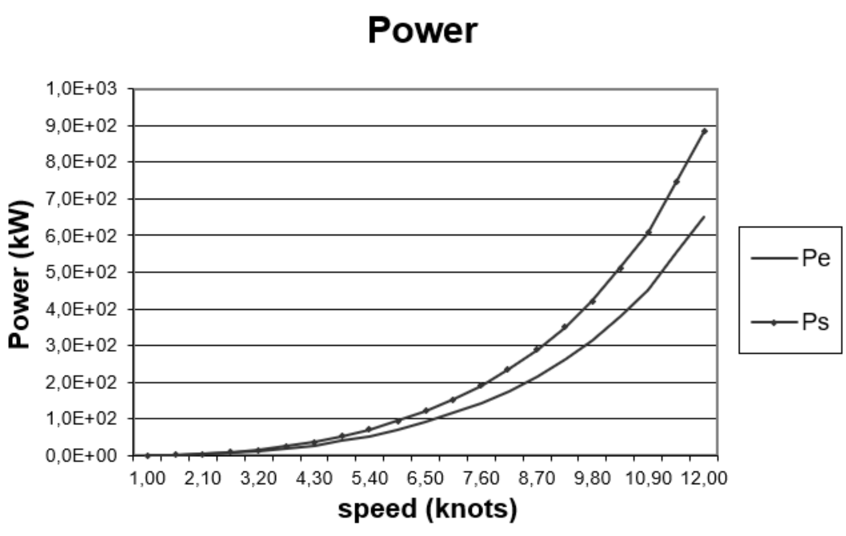


Figure 24: Power vs. speed.

The following calculations show the total energy requirement for one-way trip. During the trip Sai-MAAX is staying still for only about 2 hours. During this time, the only energy consumption comes from the hotel load of $150\ kW$. The time spent in canal outside the locks is about 5.75 hours. During this time the speed is 5 knots, and the corresponding propulsion power is about $80\ kW$. The total power requirement is thus $230\ kW$. During the trip the ship will sail at 12 knots for 14.25 hours. During this time the total power consumption is $1034\ kW$. After integrating the operating profile chart, we find that the total energy requirement for one-way trip is $16\ 360\ kWh$.
To add some energy buffer for unexpected events and winter navigation, the team settled on $45\ MWh$ total energy.

Liquid hydrogen is assumed to have energy density of $2.35\ kW/l$. Modern PEM-type fuel cells have an electrical efficiency of about 50%. With that efficiency a total capacity of $\frac{45000}{2.35 \cdot 0.5} = 36m^2$ is required. Because liquid hydrogen has much lower boiling point than LNG, $300mm$ insulation thickness is not sufficent and $500mm$ was used instead. Target volume of $36m^2$ is reached by using two type C tank with $7000\ mm$ length and $3000\ mm$ diameter. Two tanks are preferred over single tank for redundancy, better strength, and practical arrangement reasons.

Propulsion

The primary fuel of Sai-MAAX is hydrogen, which is fed to fuel cell system. Several solutions are already available for marine applications, including the Ballards *FCWave.* It combines all the required balance-of-plant functions into neat, $200\ kW$ modules measuring $1220\ \times\ 738\ mm$. Some clearance will need to be reserved for cabling, intake and exhaust gases. Certain types of fuel cells are very sensitive to impurities in intake air, so additional air purification equipment needs to be installed to prolong the service life of the cells.

Additionally, $\mathbf{1000\ kWh}$ battery set with output power of about $100\ kW$ is installed in deckhouse area to provide redundancy power generation.

Sai-MAAX will have a single electric propulsion engine with the power output of $1500\ kW$ in order to accommodate the requirements of the operating profile, which is detailed above.

The propulsor has been selected and scaled from ABB marine catalogue, from $1000\ kW$ motor we deduce a power output of $1500\ kW$, length of $3514\ mm$, width of $1425\ mm$, height of $1753\ mm$, and motor mass of $6410\ kg$.

Machinery

The power transmission of Sai-MAAX will utilize multiple modes of electricity generation to power the electric propulsion engine, including solid/liquid fuel cells, LNG, and battery packs in order to power the operating profile and ice loads. An ABB industrial drive will support all the power transmissions, with an ACS2000-series electric drive to power the $1500\ kW$ motor. The rest of the machinery is summarized in the Table 6 below.

Table 6: Summary of machinery components.

Component	**Weight**	**Quantity**	**Length**	**Height**	**Width**	**Footprint**

Motor	6410	1	3514	1753	1425	3.514 x 1.425m
Electric drive	5920	1	4350	2650	1200	4.350 x 1.200m
Fuel cells	875	7	1220	2200	738	1.220m x 0.738m
Sewage	-	1	1890	1180	1400	1.890m x 1.400m
Air handling	-	1	790	600	590	790m x 590mm
Batteries	6400	1	1000	1500	3000	3000 x 1000mm

Equipment

Select and list the required equipment for your ship considering its mission. Define/present the properties (size, weight, etc.) of the main pieces of equipment. The main equipment to be used on Sai-MAAX is listed in the Table 7 below with size and weight estimates.

Table 7: Summary of equipment.

Equipment	**Number**	**Size**	**Weight**
Anchor	2	-	1000 kg
Anchor chain	2	400 m	30 kg/m
Anchor windlasses	2	1500 x 800 x 1500	1500 kg
Mooring winches	4	1000 x 600 x 1000	500 kg
Roller	6	400 x 400 x 500 m	100 kg
Davit Lifeboat	1 1	- 5800 x 2360 x 3100	1000 kg 3265 kg
Fairlead	8	1000 x 300 x 1000	100 kg

Taking the machinery and other equipment into account, the general arrangement of the main deck can be updated as shown in the Figure 25 below.

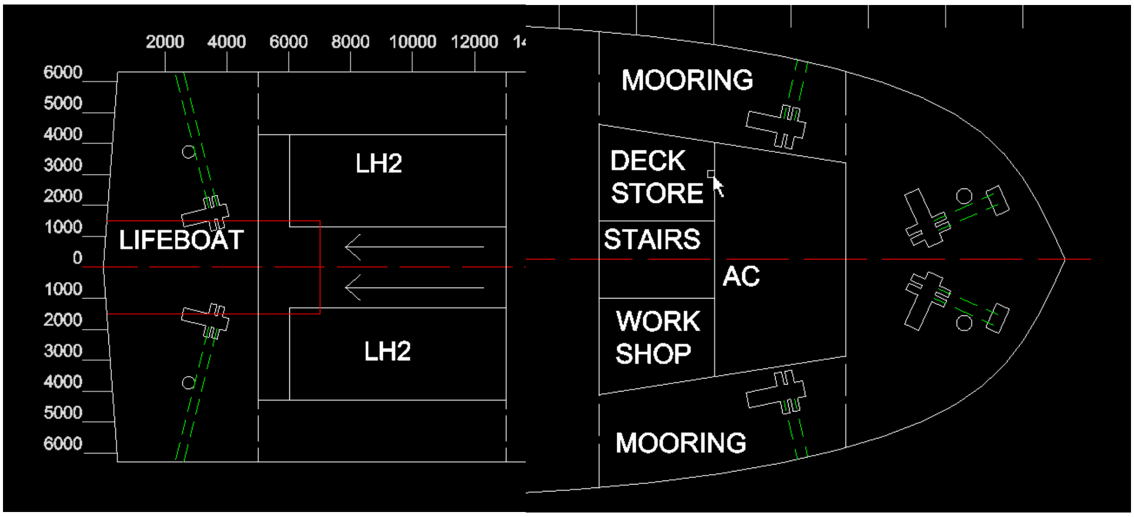


Figure 25: Main deck general arrangement with machinery and other equipment.

Weight & Stability assessment

Method 1: empirical (as per lecture notes)

The empirical method of weight estimation is shown in the following figures. The values presented were calculated using the spreadsheet provided to the class. Figure 26 shows the distribution of the weight among different components of the ship, while Figure 27 contains the calculation results themselves. The main categories were followed and correction factors were applied for the weight of the superstructure based on the assumption that composite materials would be used instead of traditional steel so they are 60% lighter and increase the DWT for the same displacement.

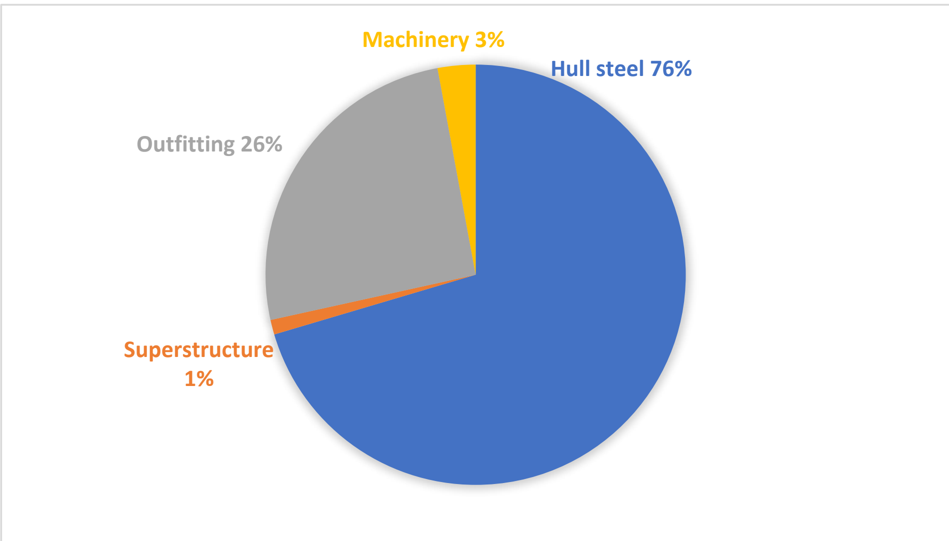


Figure 26: Overall weight distribution according to empirical method.

Ship's main characteristics	
L(m)	93.1
B(m)	12.6
T(m)	4.45
D(m)	6.8
CB	0.745
LCB(m) @AP (m)	44.22
Lightweight w/comp	
1224.20	
KGLight w/comp	
3.992	

Structural weight	
Length of superstructure (m)	9.00
Height of superstructure (m)	5.60
Length of deckhouse (m)	5.00
Height of deckhouse (m)	2.80
E	1827
K	0.032
WS (tonne)	892.62
KG_{hull} (m)	3.329
LCG_{hull} (m)	44.07
Composite correction factor	0.6
WS (tonne) w/ comp ss	871.4219
E(new)	1794.658
KG_{hull} w/ comp ss (m)	3.162556

Category	Value	Percentage
Hull steel	871	71.2%
Superstructure	14	1.1%
Outfitting	316	25.8%
Machinery	36	2.9%

Outfitting weight	
Co	0.27
W_o (tonne)	316.7
KG_o (m)	8.05

MACHINERY	
KG3	7.8
KG1	2
KG2	5
Single FC weight	0.875
Amount of FCs	7
Transformer weight	6.41
Motor weight	5.92
Aux equipment	5
Batteries	6.4
Shafting	5
Propeller	1.2
KG_M (m)	4.06
W_M (tonne)	36.06

Figure 27: Weight calculations in empirical method.

In summary for the empirical method, we see that the lightship weight is approximately 1224 tonnes which agrees within 3.4% of the SFI method which is calculated in the next section. We can estimate these values which are then used to inform future design cycles and if there are discrepancies in the other rounds they will be corrected and the lightship weight will become higher fidelity and more accurately reflect what the final weight will be.

Method 2: direct

The estimation of the ship's weight using SFI method is shown in the Figure 29 below, as well as the summary of the weight distribution in the Figure 28. The main categories were followed per recommendations and the weights of each individual component are estimated in tonnes following vendor information sheets, industry empirical evidence, and engineering judgement. At this point of the design cycle, we estimate that our final lightship weight is within 20% of the final value due to various uncertainties of the technology onboard Sai-MAAX. For example, the composite superstructure and hold hatches are unknown exactly how much weight savings will be realized.

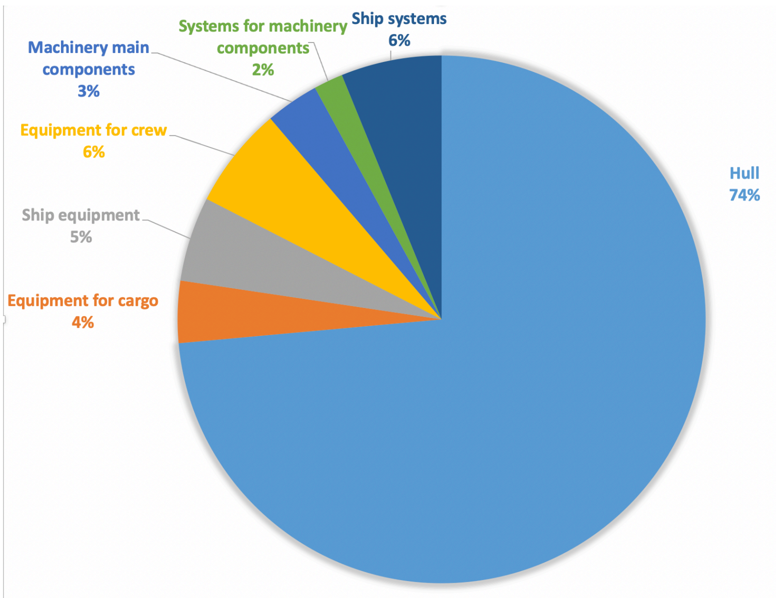


Figure 28: Weight distribution according to SFI.

Level 1	Level 2	Category	Weight [tonnes]	Reference
1		**Ship general**		
2		**Hull**	871.42	from weight estimation spreadsheet
2	0	Hull materials	857.00	
2	1	Aft body	0.00	
2	2	Engine area	0.00	
2	3	Midship/cargo area	0.00	
2	4	Fore body	0.00	
2	5	Superstructure and deckhouse	14.00	Composite estimation
2	6	Hull outfitting	0.00	
3		**Equipment for cargo**		
3	0	Hatches	40.00	
3	1	Equipment for cargo	5.00	including lashing cables/chains etc.
3	2	Deck cranes	0.00	
4		**Ship equipment**		
4	0	Manoeuvring machinery and equipment	20.00	Thruster, rudder, steering gear, control
4	1	Navigation equipment	2.00	Radar, GPS, echolocating
4	2	Communications equipment	1.00	Radio, telephone, lights
4	3	Anchoring mooring equipment	32.40	anchor plus mooring
4	4	Repair and cleaning equipment	5.00	Elec/mech workshop, spares, cleaning
4	5	Lifting and transport equipment for machinery components	1.00	Small cranes in engine room
5		**Equipment for crew (Aaron)**		
5	0	Lifesaving equipment	6.00	lifeboat + davit
5	1	Insulation, panels, bulkheads, doors, side scuttles and windows	20.00	window estimate 37.5m^2 x 14.7kg/m^2
5	2	Internal deck covering, ladders, steps, railing	10.00	10 stairwells at 50 kg each plus coverings and rails
5	3	External decks	2.00	waterproof decking for 250m^2
5	4	Furniture and inventory	4.50	inventory/supplies = 0.1t*(person*days)
5	5	Galley, pantry	0.75	provisions = 0.01t*(person*days) from lecture notes
5	6	Transport equipment for crew	0.50	gangway for boarding/unboarding
5	7	Ventilation, air condition, heating systems	15.00	air conditioning, pipes, heating resistors, warm water
5	8	Sanitary system and equipment	15.00	sewage treatment, rev.osmosis,pipes
6		**Machinery main components**		
6	1	Propeller plant, transmission	6.20	
6	2	Propulsion machinery	20.00	electric motor, transformer/drive, fuel prep & pumps
6	3	Energy systems	12.50	fuel cells, batteries
6	6	Emergency generator	0.00	
7		**Systems for machinery components**		
7	1	Lube oil system	0.00	
7	2	Cooling system	5.00	For fuel cells
7	3	Compressed air system	3.00	
7	4	Exhaust system	0.50	For fuel cells
7	6	Distilled and make up water systems	12.75	0.17t*(persons*days) from lecture notes
7	9	Automation system for machinery and cargo systems	0.00	
8		**Ship systems**		
8	0	Ballast, bilge and drain systems, scupper pipes outside	20.00	
8	1	Fire and lifeboat alarm systems, fire fighting systems	8.00	Pumps, pipes, sprinkler system
8	2	Air and sounding systems	1.00	
8	3	Special common hydraulic oil systems	1.00	Wipers, hatches?,boats,serv.cranes,etc
8	4	Electric systems, general	0.00	
8	6	Electrical supply system	10.00	Shore conn., transformers, battery support
8	7	Electrical common distribution	5.00	Switchboards, feeders etc.
8	8	Electrical cables and installation	20.00	Assuming 2km of high voltage, rest regular
8	9	Electrical distribution system	8.00	
			1184.10	**tonnes**

Figure 29: Weight estimation according to SFI.

Cost analysis

Construction costs

Building cost includes material costs and the labor. Material cost estimations were made based on the main SFI categories from last week's assignment. We used the same SFI spreadsheet, which made it easier to estimate each subcategory separately. These main categories can be seen in the Figure 30. The costs were estimated based mainly on the literature research, as it is difficult to find full data on the ship building costs.

Category	Cost
Hull	1 449 000 €
Equipment for cargo	900 000 €
Ship equipment	658 000 €
Equipment for crew	770 000 €
Machinery main components	2 000 000 €
Systems for machinery components	500 000 €
Ship systems	1 500 000 €
TOTAL	**7 777 000 €**

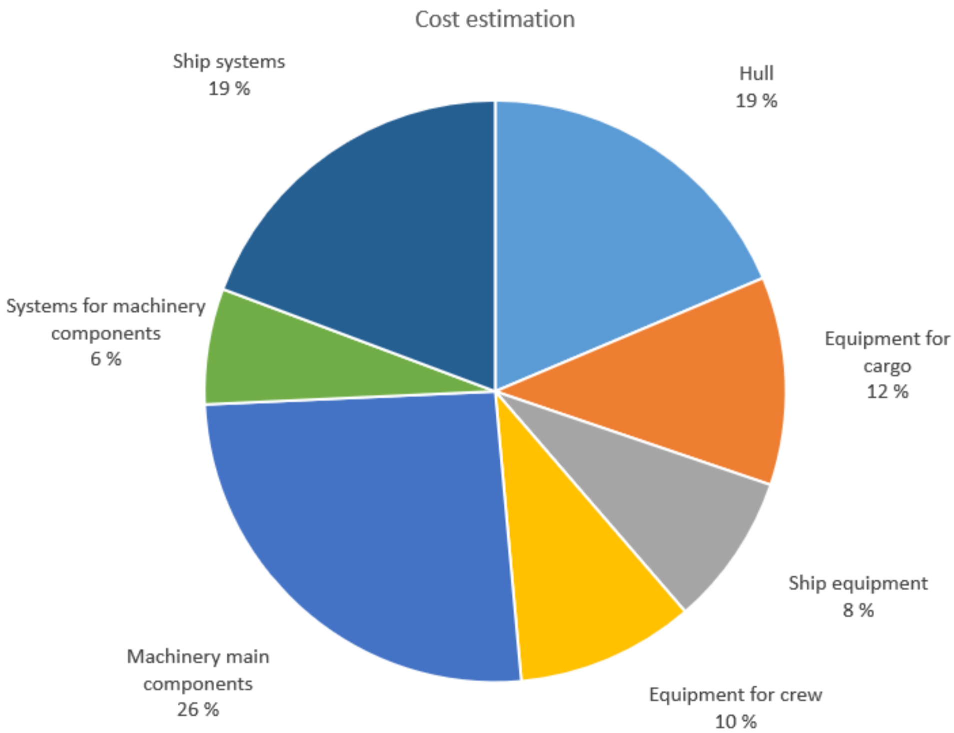


Figure 30: Costs estimation and their proportions.

Economic performance

Assuming the 11 months of operating and 200 operating days. Based on the earlier calculations, daily fuel consumption should be around $1250\,kg$. If the liquid hydrogen fuel would be produced cleanly near the refuelling facility, the optimistic reflected cost is 5 €/kg. Electricity for shore operation and battery power is considered to be 100 €/ day. Seafarers Union of Russia suggests that average wage for crew is about 100€/day. For the owner, we assume that the crew cost is twice the salary.

Net tonnage is based on assumption that cargo space is $3000m^3$ (about 80% from displacement). Load Lines Convention formula gives a rough net tonnage of $\mathbf{630.}$ According to Finnish customs, for Ice class 1C ships the fairway due is $2.578 \cdot NT = \mathbf{1623}$€. Port dues are estimated based on HaminaKotka documents. The summary of the daily running costs is presented in the Table 8:

Table 8: Daily costs estimation breakdown.

BREAKDOWN	**DAILY COST (EUR)**
Fuel costs	6250
Fuel cell wear	1200
Crew (10)	2000
Supplies	500
Maintenance	250
Fairway dues	1623
Port dues	600
TOTAL OPERATING	**2750**
TOTAL VOYAGE	**9673**

Economic KPIs

The most relevant KPIs for this project are net present value and required freight rate. The results of the spreadsheet calculation are shown below.

Interest rate	Operating days	Daily operating cost	Daily voyage costs	Yearly operating	Yearly voyage	Building cost	Revenue	DWT
0,10	200	2750	5873	1089750	1934900	7777000	4112000	2570

Year	Cash flow	NPV	PROFIT MARGINS	FREIGHT RATE
0	-7777000	-7777000	1179660	8
1	1066555	-6710045	30,94	
2	969639	-5740007		
3	881741	-4858406		
4	801619	-4056887		
5	728744	-3327943		
6	662495	-2665448		
7	602268	-2063180		
8	547516	-1515664		
9	497742	-1017922		
10	452498	-565429		
11	411357	-154072		
12	372951	219889		
13	339465	559854		
14	308599	868913		
15	280052	1143875		
16	255420	1405296		
17	232200	1647096		
18	211091	1848587		
19	191901	2040488		
20	174456	2214944		

Net present value (NPV) takes the compound interest into account and when it is zero, the owner breaks even. The formula for calculating NPV is presented below:

$$NPV = -C_0 + \Sigma_{i=1}^{n} \frac{C_1}{1+r}$$

In NPV calculation, we used an interest rate of 10%. The operating costs were annualized, with the assumption of 200 operating days.

Required freight rate (RFR) describes the rate that the owner needs to charge for the cargo to break even and the formula for it is presented below.

$$\mathrm{RFR} = \Sigma_{i=1}^{n} \left[\frac{\text{Present value of operating costs} + \text{Present value of acquisition costs}}{\text{Cargo tonnage}} \right]$$

For these calculations, a cargo capacity of 2450 tons was used, since hydrogen fuel is very light and the crew provisions/water requirements are tiny for such a short trips.

A very large profit margin of 31% was required to break even at 20 years of operation, translating into $\boldsymbol{RFR = 7.9}$. With freight rate of 8.4 and profit margin of 40% the ship broke even at 12 year mark and produced a gross profit of 2.25 M€ in 20 years of operation. At the end of the analysis period of 20 years, the composite structures yielded about $850\,000$ € of extra profit due to increased cargo capacity. However, this estimate excludes secondary benefits, such as alleviated maintenance, better stability, less hatch machinery etc. It is evident that for the given prices, composites are not a financial no-brainer.

The simplest way to improve the KPIs is to reduce the RFR, which is dependent on all of the costs. Considering the annualized operating costs, building costs are difficult to shave from.

That being said, more mature composite industry could reduce the price of those components and make them profitable earlier. Automation is a major cost saving factor, since it greatly reduces the crew costs and also costs of support machinery. Outsourcing the crew from Southeast Asia would also reduce this cost, but due to ethical reasons the design team opted for local crew. Special cargo handling equipment both in shore and onboard can be used to increase the days spent at sea, though careful assessment of their economic soundness should be conducted as well. To minimize the part-loading of the vessel, 8-16 20ft TEU can be fit on rear deck and thus more income gained on those situations. Of course, a natural way to increase the profitability is to ensure the absolutely best loan deal: a reduction of 1% leads to 700 000 € increase in profits in 20-year period. Alternatively, a fixed-income loan can be a lottery win or a disaster, depending how the interests evolve in future.

Project evaluation and conclusions

SWOT

Due to being a new type of zero-emission ship, Sai-MAAX faces multiple variables and risks compared to more conventional vessels. The main strength of Sai-MAAX is its zero-emission operating, which is made possible by hydrogen-based fuel cells. While this is an important factor in the modern world, where fighting climate change is a major target, it also comprises some weaknesses and threats. These are listed in the SWOT analysis Table 9 below.

Table 9: SWOT analysis.

STRENGTHS	WEAKNESSES
• Ice breaking capability • Environmental friendliness • Strong support from government • Cargo flexibility	• High cost of hydrogen • High crew cost • Lifetime of fuel cells and batteries • Availability of hydrogen
OPPORTUNITIES	**THREATS**
• Forest industry in the area • Inland waterway transport is cost-efficient compared to road transport • Generally Finnish inland vessels are old • Renovation work of Saimaa canal	• Canal dues increasing • Trade & mobility restriction between Russia and Finland • Experimental propulsion system • Draft and range narrow flexible usage of the vessel in the case of changes in business environment • Dangers of hydrogen

Discussion

The team settled to conventional icebreaking design at very early phase of the design, but additional more effective methods were unraveled along the way. These included double-acting design and detachable ice-breaking bow, both of which allow for a much greater block coefficient and more competitive freight rates. Due to lack of experience the bow shape was likely exaggerated, allowing for even higher ice-breaking capacity than needed. Considering the ever-warming winters in the area, this phase of the design clearly needs heavy revising.

Hydrogen fuel cell propulsion was the biggest innovation in the project. The technology exists, though no projects of this size have been completed and reliable data extracted from them. A certain degree of hope in the future was included in key parameters and cost analyses. As the push for green transportation accelerates, support from the government and EU could very likely be received. Of course, hydrogen requires substantial investment to refuelling/production facilities as well, again deterring investors. To make matters worse, even additional fueling stops might be needed since handling gaseous fuel near people is not an option. The other major innovation was composite construction. Their success largely depends how the prices will evolve and how the regulations allow these materials. Automations were excluded for the sake of simplicity, but obviously the owner would want to shave from operating costs and this would be a good way to cut from the crew. Either way, evaluating the economics of this project as an conventional cargo ship is inappropriate due to its pioneering nature.

The swiftness of port stays makes a huge difference in competitive shipping industry. The team settled for a crane-free system with movable bulkheads, as per suggestions by mentor. When handling labor-intensive timber cargo, however, onboard cranes would definitely be useful despite the weight penalty.

In the next iterations the structural details need to be analyzed in greater detail. Shear stresses were excluded from this report for the sake of simplicity, but as the hold openings introduce major shears to structure, it is of paramount importance to include these calculations in further refinements.

In the end, the viability of the design depends entirely on the industries in the area: should the Lappeenranta’s exports cease to be attractive, the ship would be dead-on-arrival. Bilateral long-term policies and agreements between Russia and Finland might be needed before any investor would dare to invest to such a niche vessel. As a mixed-navigation vessel the ship stands at a peculiar place, where it is like too heavily built to thrive in purely inland environment and on the other hand has a too short range and efficiency to prosper in coastal environments elsewhere.

Team member comments

Juho Suortti

For me, this project was a really interesting way to put all the bits of information acquired at work into context. Additionally, constraints imposed by the design mission meant that some exciting novel solutions could be realistically implemented. Class requirement and stability considerations were left largely untouched or to the team's own responsibilty, but this is understandable due to already massive breadth of the course. All in all, I feel much more confident on my skills and I believe that after seeing the impact of various disciplines on the ship design, I'm able to rationalize my future studies a bit better.

Johanna Myllymäki

I find the course and project very interesting, but slightly more demanding and much more time consuming than I assumed. However, the course and the project helped me to gain a knowledge that will improve my competence in the future. It is quite common that technical specialists working in ship design and shipbuilding projects are lacking the basic knowledge of naval architecture. This course has provided me a fast lane to better understand the roles of different disciplines and more clear and professional manner to communicate about the details in ship projects.

Viljami Erkkilä

I am very glad I took this course in the beginning of the first semester of my master's studies. Before this course I mainly had some very basic knowledge about hull designing, but during this course I acquired a lot more understanding on the ship designing process. Going through the design spiral was challenging some weeks, but the best learning outcomes often come from pushing through the difficult tasks. I am more confident in continuing my studies after this course.

Anna Nikitina

This course was quite challenging for me, or at the very least it required more effort than I expected. Even though I have been studying mechanical engineering for a few years now, my focus and interest is mostly lying on mechatronics and simulation side, so sometimes it was difficult to draw direct connections to what I have been doing before. However, I learnt a lot of new things and discovered another interesting field of engineering that I might explore more in the future from more theoretical side. But already now I can see how the knowledge about the ship design I got from this course benefits my day-to-day job, where I need to communicate with the customers in port industry. I hoped that I could implement my knowledge of mechatronic systems here, but during the course I understood that the design of systems like I am used to for a vessel goes beyond the initial design implemented during this course.

Aaron Körkkö

I enjoyed working on this project with the team and learning new concepts each week was quite a challenge. With changing schedules and workloads we managed to achieve the requirements each week set out by the corresponding course and I think that is a sign of a successful project. It was interesting to have an evolving design concept each week and to split up the work, but at the end of it I would not change the group dynamic because we seemed to work well. I would like to study many of the concepts introduced in this project and course further.

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