# Conceptual Study on Maximum Allowable Lengthening for a 4629 DWT Tanker to Enhance Cargo Capacity and Convert to Dual-Fuel LNG/Diesel Propulsion

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## Abstract

This study examines the midsection lengthening of a 4629 DWT tanker by adding proportional segments equivalent to the length of one tank. The still water bending moment of the original ship was estimated, and the combined bending moments for different scenarios in unrestricted waters were analyzed using MaxSurf. The original sectional modulus was calculated and compared using POSEIDON software, as well as the formulas provided by ABS and DNV for longitudinal strength assessment. To reduce $CO_2$ emissions, a dual-fuel propulsion system was proposed, taking advantage of the additional space made available by the lengthening. The EEXI of the original engine, the EEDI of the LNG-powered engine, and the CII were calculated, demonstrating notable emission reductions. As part of the optimization proposal, the tanker's cargo capacity was increased, revealing the potential to boost revenue per voyage while simultaneously improving maritime routes through reduced emissions. Lastly, a structural and propulsion analysis of the lengthened vessel was performed using the Campbell diagram. The natural frequencies of the ship's beam were estimated with POSEIDON, identifying critical zones and potential resonances that could impact structural integrity.

**Key words:** Midsection lengthening, longitudinal strength, POSEIDON, dual-fuel propulsion, EEXI (Energy Efficiency Existing Ship Index), CII (Carbon Intensity Indicator), Campbell diagram, potential resonances.

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## Introduction

This study examines the maximum allowable midship lengthening of a 4.629 DWT double-hull tanker ship using data from the *(Loading Manual, 2008)* and evaluates the transition from an HFO system *(Ship Technical Report, 2023)* to a dual-fuel propulsion system to reduce $CO_2$ emissions.

The analysis assesses the midsection's web frame is done by comparing it with the "Minimum Section Modulus" recommended by the Classification Societies *(ABS, 2022 and DNV, 2023)*, calculates the bending moment under various loading and wave conditions for different lengthenings of the tank sections, and determines the required sectional modulus. It also estimates the natural frequencies of the bulkhead structures using *(POSEIDON, 2023)* and compared them with the excitation frequencies generated by the propeller and the main engine, utilizing the Campbell Diagram *(Ren, 2023)* to identify potential structural resonances.

Ship lengthening offers advantages such as increased cargo capacity, reduced operating costs, improved hydrodynamic efficiency, and enhanced speed. LNG as a marine fuel, driven by its energy efficiency and lower emissions, is increasingly adopted in compliance with environmental regulations like ECA *(IMO, 2024)* and DECA *(Yang, 2022)*.

The proposed lengthening is presented as a feasible approach based on structural evaluations, aiming to enhance cargo capacity while meeting *(DNV FUELEU Maritime, 2024)* objectives. Transitioning from an HFO engine to a dual-fuel LNG/Diesel propulsion system aligns with stricter environmental standards, improving energy efficiency and reducing $CO_2$ emissions.

## Methodology

### Permissible Lengthening Based on Section Modulus Calculations

Longitudinal continuous components were identified as the structural elements involved in the Section Modulus calculation. The Minimum Section Modulus was determined by relating the Sectional Moment of Inertia to the greatest distance from the neutral axis, which, in this case, corresponded to the main deck *(SNAME, 2003)*.

$$\text{Min. SM} = \frac{\text{Sectional Moment of Inertia}}{\text{Centroid towards deck}}, \quad [m^3] \tag{1}$$

The main dimensions of the original tanker ship and the different proposed lengthenings were presented. These lengthenings were considered based on the length of the cargo tank, measuring 13,86 m, located in the midship.

**Table 1. Characteristics and proposed lengthenings.**

| | | |
|---|---|---|
| **Original Length** | 90,22 | [m] |
| **Beam** | 15,60 | [m] |
| **Draft** | 6,00 | [m] |
| **Depth** | 7,80 | [m] |
| **Original DWT** | 4.629 | [ton] |
| **Original Displacement** | 6.484 | [ton] |
| **Length of section of tank** | 13,86 | [m] |
| **Lengthening 1 section** | 104,08 | [m] |
| **Lengthening 2 sections** | 117,94 | [m] |

**Fig. 1. Proposed lengthening of 1 section.**

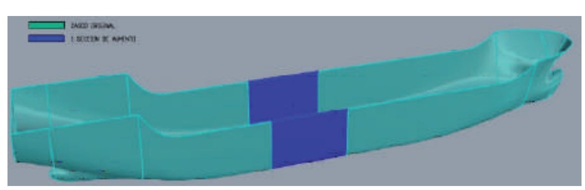
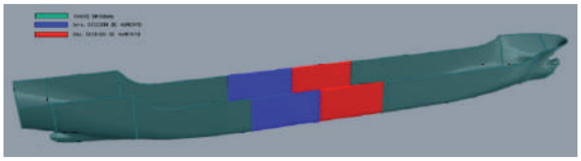


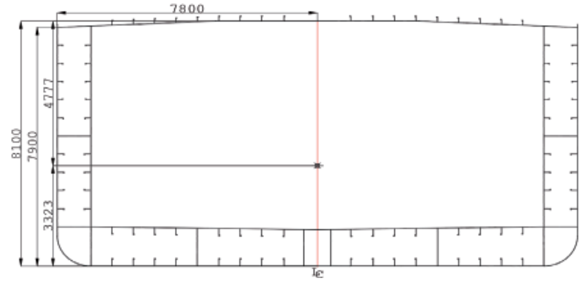
**Fig. 2. Proposed lengthening of 2 sections.**



The midsection's web frame was drawn at full scale in AutoCAD, including its actual dimensions, plating thicknesses, and continuous longitudinal reinforcements. Using the MASSPROP command, the Moment of Inertia and the centroid, measured from the deck, were calculated. Equation (1) was then applied to determine the Minimum Section Modulus.

Additionally, the optimized tanker ship lengthened by one section was structurally modeled in the *(POSEIDON, 2023)* software to calculate the Minimum Section Modulus according to *(DNV, 2023)* Classification Society.

**Fig. 3. Midship's Web Frame drawn with AutoCAD.**




Section Modulus was also related to the maximum bending Moment that the ship could withstand and the permissible stress for standard naval steel *(DNV, 2023)*.

$$SM = \frac{\text{Combined Moment}}{\text{Allowable Stress}}, \ [m^3] \quad (2)$$

For the analysis of the maximum bending Moment of the original tanker ship, information was gathered from the loading manual provided by the ship designer

**Fig. 4. Tanker ship modeled using DNV-POSEIDON.**

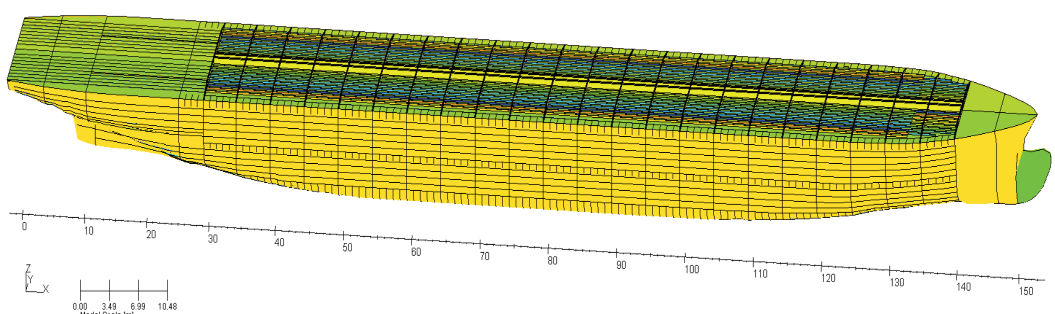



**Fig. 5. View from the main deck.**

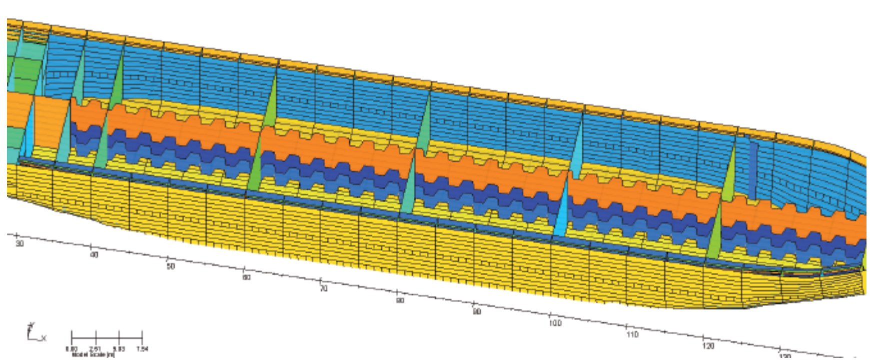
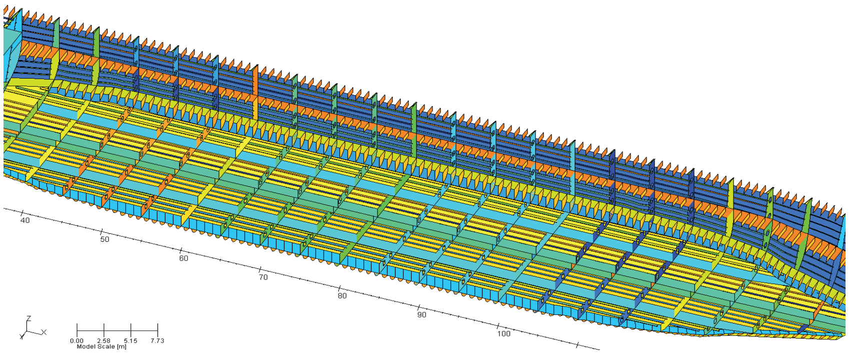


**Fig. 6. View from the bottom.**




*(Loading Manual, 2008)*. The selection of the critical scenarios was based on the most unfavorable still water conditions identified in the manual. The two most critical Moments for still water conditions and their respective longitudinal positions were estimated, with the maximum recorded as 110.862 [kN·m] in Hogging. These values were selected as they represent the most several loads under still water conditions, ensuring a conservative approach in the structural assessment.

**Table 2. Critical still water Moments as provided by the Loading Manual of the original tanker ship.**

| Condition | Position [m] | Bending [kN·m] |
|---|---|---|
| L022 Ballast Condition Arrival | 42,78 | 77.363 |
| L131 Slop tank full rest empty condition departure | 36,18 | 110.862 |

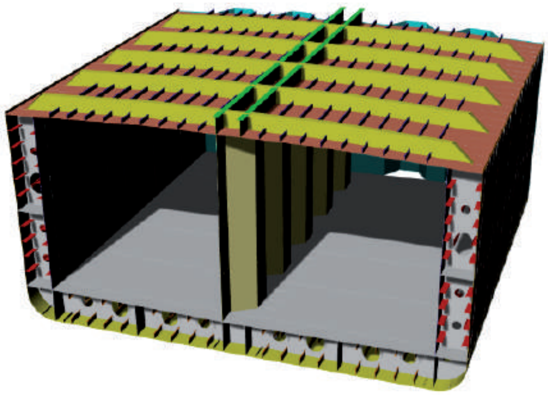
Based on the information from the loading manual *(Loading Manual, 2008)*, the MaxSurf software was used to input all weights along with their respective centroids in three dimensions, as well as the tank filling status for the critical L131 condition. This condition was selected considering the most unfavorable scenario described in the loading manual, ensuring that the structural analysis accounted for the maximum expected operational stresses. This procedure in MaxSurf allowed verification of the still water bending moment reported in the loading manual and, subsequently, the calculation of the Wave Bending Moment for a sea state 6 *(CENTEC, 2015)* and the maximum combined Bending Moment.

The selection of a sea state 6 is justified by its correspondence with severe navigation conditions, representative of demanding operational scenarios in transoceanic routes. Considering these dynamic loads is essential for evaluating the structural strength of the ship under real service conditions, ensuring that the structure can withstand the stresses induced by wave action without compromising its integrity.

Using the same procedure with MaxSurf, the Moments for the two proposed lengthenings of the tanker ship were calculated. The Bending Moments were then determined according to *(DNV, 2023)*, where the coefficients used in this study were based on DNV recommendations for strength assessment.

Following the same procedure in MaxSurf, the bending moments were calculated for the two proposed lengthening scenarios of the tanker ship. It was assumed that the weight redistribution and the additional cargo capacity maintained a distribution similar to that of the original ship. The bending moments were then determined according to *(DNV, 2023)*, where the coefficients used in this study were based on DNV recommendations for structural strength assessment [1]:

**Fig. 7. 3D view of a section for the lengthenings.**



$$M_{wv-h} = 0{,}19 * \frac{f_R}{0{,}85} * f_{nl-vh} * f_m * f_p * C_W * L^2 * B * C_B \,, [kN \cdot m] \quad (3)$$

$$M_{wv-s} = -0{,}19 * \frac{f_R}{0{,}85} * f_{nl-vs} * f_m * f_p * C_W * L^2 * B * C_B \,, [kN \cdot m] \quad (4)$$

The Required Section Modulus, according to the Classification Society *(DNV, 2023)*, was calculated using Equation (2). Additionally, it was also calculated following the guidelines of the Classification Society *(ABS, 2022)*. [2]:

$$SM = C_1 * C_2 * L^2 * B * (C_B + 0{,}7), \ [m-cm^2] \quad (5)$$

**Table 3. Original tanker ship.**

| Description | Value | Units |
|---|---|---|
| BkW | 2.480 | [kW] |
| Δ | 6.484 | [ton] |
| DWT | 4.629 | [ton] |
| Speed | 10,5 | [knots] |
| Fuel oil consumption | 188 [g/kWh] | |
| Arrangement | 8-cylinder L-engine | |
| Conversion factor | 3,114 | [g $CO_2$/g] |
| Number of blades | | 4 |
| Reduction gear box | 4,9725 : 1 | |

## Dual-Fuel LNG/Diesel Propulsion

Based on the information provided in the *(Loading Manual, 2008)*, *(Product Guide Wärtsilä, 2016)*, and the CO2 emission factor *(Ryu, 2020)*, the specifications were presented.

**Table 4. Proposed lengthening ship, *(Product Guide Wärtsilä, 2016)*. [3]**

| Description | Value | Units |
|---|---|---|
| BkW | 2.680 | [kW] |
| Δ | 7.792 | [ton] |
| DWT | 5.812 | [ton] |
| Speed | 10,73 | [knots] |
| Arrangement | 8-cylinder L-engine | |
| Conversion factor | 2750 | [g $CO_2$/g] |
| RPM Min. | 250 | |
| RPM Max. | 750 | |
| Operating RPM | 720 | |
| Stroke | 4 | |

**Table 5. Specific fuel consumption, *(Product Guide Wärtsilä, 2016)* and LCV for LNG *(IMO, 2016)*.**

| Fuel | Gas [kJ/kWh] | Diesel [g/kWh] |
|---|---|---|
| FO consumption at 85% load | 2,2 | 186 |
| FO consumption at 75% load | 2,5 | 186 |
| FO consumption at 50% load | 3,8 | 194 |

| LCV | Value | Units |
|---|---|---|
| Lower calorific value | 48.000 | [kJ/kg] |

The Energy Efficiency Existing Ship Index (EEXI), developed by the IMO, was used to assess the energy efficiency of existing ships in terms of carbon dioxide ($CO_2$) emissions per unit of transport *(ClassNK, 2022)*.

$$EEXI = \frac{CO_2 \text{ Conversion Factor} \cdot SFC \cdot P}{DWT \cdot Speed}, \frac{CO_2\,g}{[ton \cdot mile]} \quad (6)$$

The Energy Efficiency Design Index (EEDI), also developed by the IMO, was employed to evaluate the energy efficiency of newly built ships based on their $CO_2$ emissions per unit of transport *(IRCLASS)*.[4]:

$$EEDI = \frac{P \cdot SFC \cdot CO_2 \text{ Conversion Factor}}{DWT \cdot Speed}, \frac{CO_2\,g}{[ton \cdot mile]} \quad (7)$$

The Carbon Intensity Indicator (CII), established by the IMO, was used to evaluate the operational carbon efficiency of ships by measuring $CO_2$ emissions per unit of cargo transported, and distance traveled *(GreenVoyage2050, 2023)*. [5]:

$$CII = \frac{\text{Anual } CO_2 \text{ emissions}}{DWT \cdot \text{Distance Sailed}}, \frac{CO_2\,g}{[ton \cdot mile]} \quad (8)$$

## Natural Frequencies and possible resonances of the Midship's Web Frame at Midship

The natural frequencies of longitudinal plates of the web frame at midship were estimated using the software *(POSEIDON, 2023)*.

To determine the engine and propeller firing frequency according to the *(GL, 2016)*.

$$f_{ign} = \frac{K_{stroke} \cdot n_c \cdot n_e}{60}, [Hz] \quad (9)$$

$$f_{blade} = \frac{n \cdot z}{60}, [Hz] \quad (10)$$

$$f_{Max} = 1{,}2 \cdot f, [Hz] \quad (11)$$

$$f_{Min} = 0{,}8 \cdot f, [Hz] \quad (12)$$

**Fig. 8. Natural frequencies [CPS] of shell.**

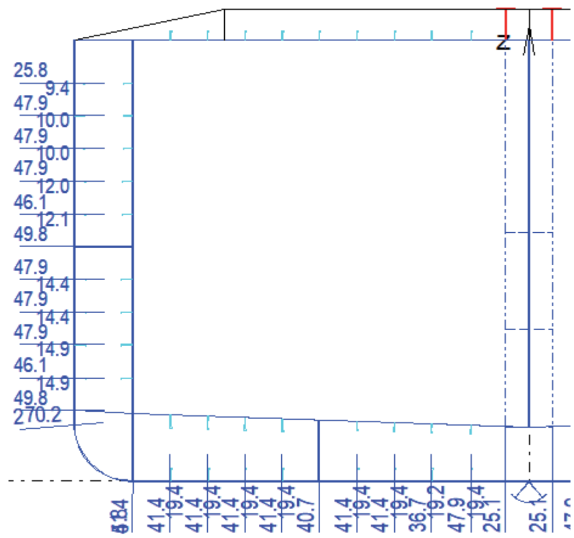
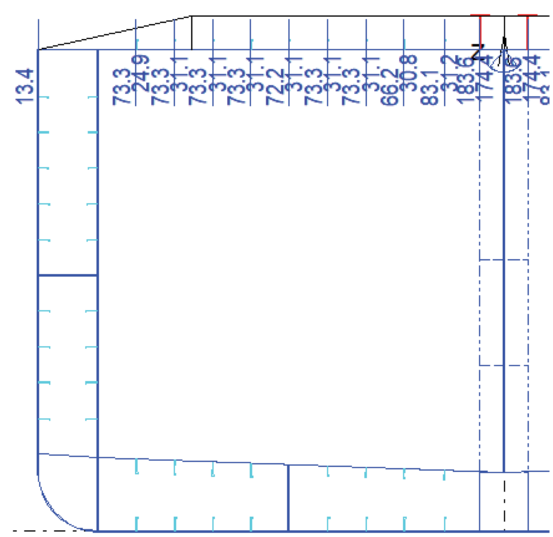


**Fig. 9. Natural frequencies [CPS] of main deck.**



# Results

## Permissible lengthening based on section Modulus calculations

Using Equation (1), the results of the analysis of the mechanical properties of the master web frame, modeled using AutoCAD, and the section modulus, calculated using DNV-POSEIDON, were presented.

**Table 6. Structural characteristics of the Midship Section and Minimum Section Modulus.**

| | | |
|---|---|---|
| **Moment of Inertia** | 10,30 | [$m^4$] |
| **Centroid Bottom** | 3,32 | [m] |
| **Centroid Deck** | 4,78 | [m] |
| **SM on Deck with AutoCAD** | 2,15 | [$m^3$] |
| **SM on Deck with DNV-POSEIDON** | 2,04 | [$m^3$] |

The result of the maximum still water Bending Moment using MaxSurf software was 111.142 [kN·m], comparing the result from the Loading Manual. Additionally, the wave Bending Moments for a sea state 6 (CENTEC, 2015) and the combined Bending Moment were obtained, illustrated in the FIg. 10.

For this load condition, the maximum combined Bending Moment was 231.542 [kN·m]. The maximum permissible Stress for steel ASTM A131 is 175 [MPa], and using Equation (2), the calculated Section Modulus was 1,32 [$m^3$]. The Bending Moments were also calculated for the two proposed lengthenings.

**Fig. 10. Bending Moments curve of the original tanker ship in the critical condition.**

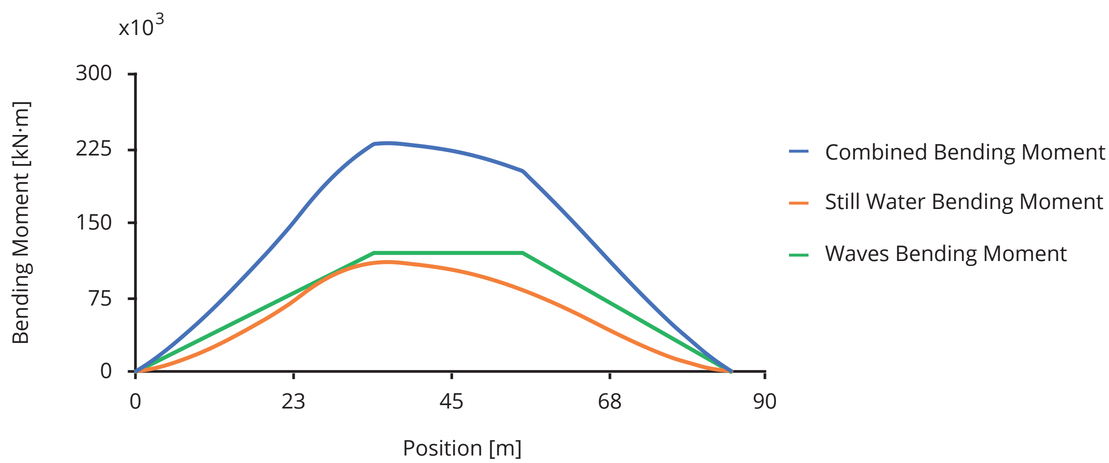
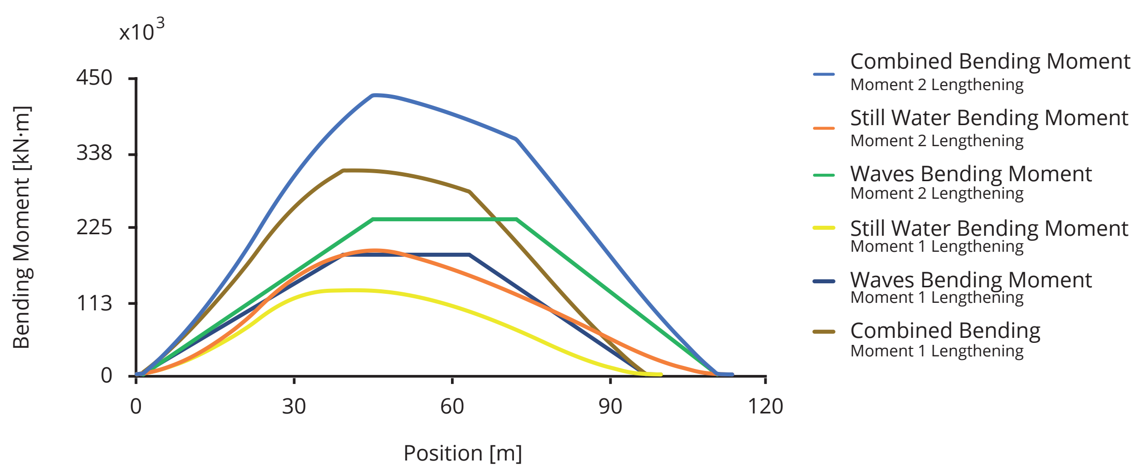



**Fig. 11. Bending Moments Curve for the proposed lengthenings of the tanker ship.**



Using the formulations from *(DNV, 2023)*, Equations (3) and (4) were applied, and the results were obtained.

**Table 7. Bending Moments Results using *(DNV, 2023)*.**

| | | |
|---|---|---|
| **L Original** | 90,22 | [m] |
| **CB** | 0,78 | - |
| **MMAX-h** | 2,48E+05 | [KN·m] |
| **MMAX-s** | -2,35E+05 | [KN·m] |

| | | |
|---|---|---|
| **L 1 Section** | 104,08 | [m] |
| **CB** | 0,80 | - |
| **MMAX-h** | 3,47E+05 | [KN·m] |
| **MMAX-s** | -3,28E+05 | [KN·m] |

| | | |
|---|---|---|
| **L 2 Sections** | 117,94 | [m] |
| **CB** | 0,81 | - |
| **MMAX-h** | 4,65E+05 | [KN·m] |
| **MMAX-s** | -4,40E+05 | [KN·m] |

**Table 8. Results of the maximum combined Bending Moments using DNV formulations and MaxSurf.**

| | L [m] | MMAX-h [KN·m] |
|---|---|---|
| **Maximum BM according to DNV** | 90,22 | 2,48E+05 |
| | 104,08 | 3,47E+05 |
| | 117,94 | 4,65E+05 |
| **Maximum BM from the loading manual using MaxSurf** | 90,22 | 2,32E+05 |
| | 104,08 | 3,17E+05 |
| | 117,94 | 4,34E+05 |

The maximum Bending Moments were calculated. The results obtained using the formulations of the vv *(DNV, 2023)* Classification Society were higher than those obtained with MaxSurf, based on the information from the Loading Manual, for the proposed lengthening of one section of the tanker ship.

Equations (2) and (5) were applied to calculate the Section Modulus for the original tanker ship and the two proposed lengthenings, following the standards outlined by (DNV, 2023) and (ABS, 2022), respectively. The results obtained from these methods, along with additional calculations performed using

**Fig. 12. Maximum combined Moments: DNV vs. *(Loading Manual, 2008)* Using MaxSurf.**

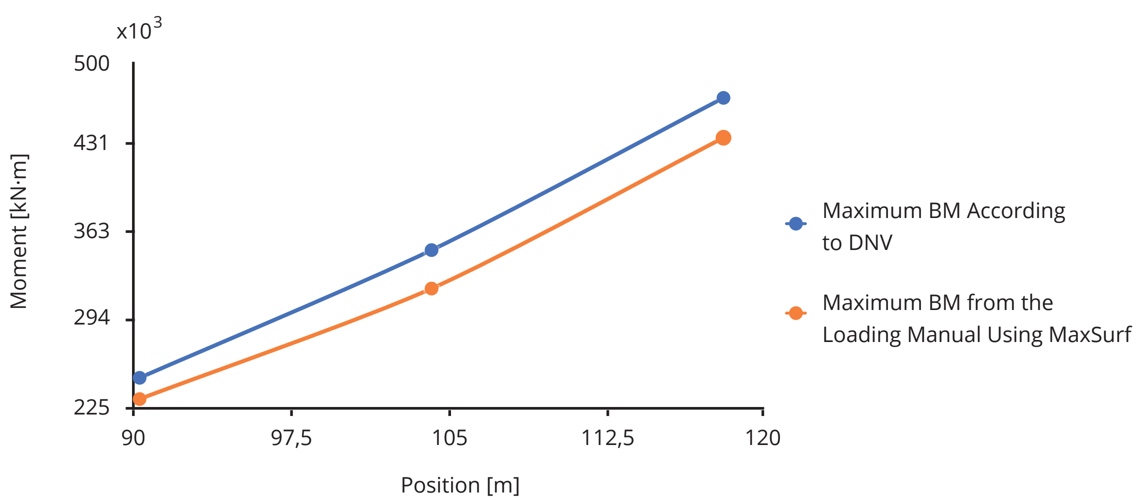


**Table 9. Results of the Section Modulus.**

| L [m] | DNV [m³] | ABS [m³] | LM [m³] | AutoCAD [m³] | Poseidon [m³] |
|---|---|---|---|---|---|
| 90,22 | 1,42 | 1,45 | 1,33 | 2,13 | 2,04 |
| 104,08 | 1,98 | 1,95 | 1,81 | 2,13 | 2,04 |
| 117,94 | 2,66 | 2,53 | 2,48 | 2,13 | 2,04 |

MaxSurf with the *(Loading Manual, 2008)*, AutoCAD, and POSEIDON software, were presented.

When comparing the still water moment result provided by the loading manual and the one calculated with MaxSurf, the percentage difference is less than 1%, which indicates that the analysis performed by inputting the weights and centroids of the ship into the generated model is accepted.

After performing the same analysis for the two proposed lengthenings and calculating the combined moment, it is observed that in Figs. 10 and 11, the moment curve shows the same behavior.

In Fig. 12, the results of the combined moments calculated by MaxSurf are lower than the maximum Moments allowed by DNV, which implies that, for the one-section lengthening, it is acceptable and remain within the limit specified by the classification society, however, lengthening with two cargo tanks was not acceptable, see Fig. 13.

## Increase in DWT for the proposed lengthenings

Table 10 shows the results for the original ship and the two proposed lengthenings.

The displacement of the original ship was verified based on the data provided by the Loading Manual and using the MaxSurf software. For the original DWT, the value provided by the Loading Manual was used.

It is worth noting that these displacement values were estimated based on a draft of 6 meters.

**Fig. 13. Comparison curve of Section Modulus and the Optimal Lengthening of tanker ship.**

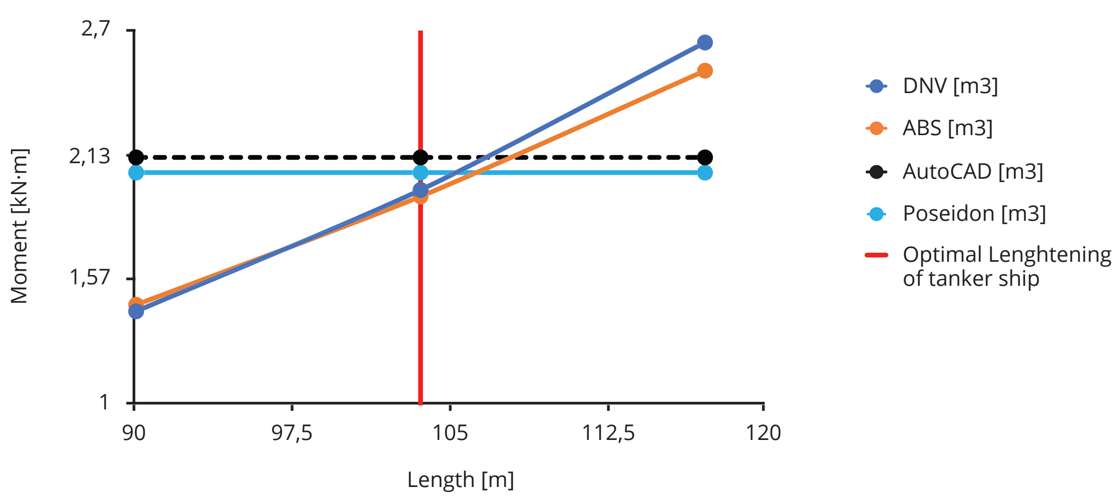


**Table 10. Results displacements and DWTs.**

| | | |
|---|---|---|
| **Δ Original** | 6.484 | [ton] |
| **T Original** | 6,00 | [m] |
| **DWT Original** | 4.629 | [ton] |
| **DWT (Only 1 Section)** | 1.183 | [ton] |

| | | |
|---|---|---|
| **Δ (L. 1 Section)** | 7.792 | [ton] |
| **T (L. 1 Section)** | 6,00 | [m] |
| **DWT (L. 1 Section)** | 5.812 | [ton] |

| | | |
|---|---|---|
| **Δ (L. 2 Sections)** | 9.130 | [ton] |
| **T (L. 2 Sections)** | 6,00 | [m] |
| **DWT (L. 2 Sections)** | 6.995 | [ton] |

The DWT of one section was estimated based on its volume, which was modeled in detail in Rhinoceros (Fig. 7). Using this DWT value for one section, the DWT for the proposed lengthenings of one and two sections was estimated.

For the proposed lengthening of one section, the displacement increased by 20%, while the DWT increased by 26%.

For the proposed lengthening of two sections, the displacement increased by 41%, while the DWT increased by 51% compared to the original tanker ship.

Based on the study of the midship section modulus, the tanker ship can structurally withstand up to one proposed lengthening. Therefore, this modification would allow for up to a 26% increase in cargo capacity.

In addition to the optimization of operational efficiency resulting from the increase in DWT, the additional space generated by the lengthening could allow for the installation of LNG tanks on deck, potentially increasing the ship's autonomy.

## Dual-Fuel LNG/Diesel Propulsion

The following table presented the results of the EEXI and EEDI energy efficiency indices for the proposed lengthening of one section, using Equations (6) and (7).

**Table 11. EEXI and EEDI for the system propulsions.**

| | **[CO2 g / ton·mile]** | **Type of fuel** | **Type of engine** | **DWT** |
|---|---|---|---|---|
| EEXI | 30 | HFO | Original | 4.629 |
| EEDI | 22 | 85% FO | Dual Proposed | 5.812 |
| | 20 | 75% FO | | |
| | 17 | 50% FO | | |

Based on Table 11, the EEDI result for the proposed dual-fuel LNG/diesel system propulsion with new power and the new DWT of 5.812 tons shows that for the 85% FO and 15% LNG proportion, there is an 27% reduction in $CO_2$ emissions per ton transported one mile. For the 50% FO and 50% LNG proportion, the reduction reaches 43%.

**Table 12. Results of the original tanker ship and the optimized ship lengthened by one section.**

| **Parameter** | **90,22 m** | **104,08 m** | **Improvement %** |
|---|---|---|---|
| **DWT [ton]** | 4629 | 5812 | 26% |
| **[CO2 g / ton·mile]** | 30 | 22 | 27% |
| | | 20 | 33% |
| | | 17 | 43% |

Table 12 presented the comparison between the original ship and the proposed ship lengthened by one section. The results showed a 26% increase in DWT, reaching 5.812

tons. Additionally, $CO_2$ emissions per ton-mile were reduced from 27% up to 43%, depending on the LNG-fuel mix. These improvements demonstrated the benefits of the lengthening in terms of cargo capacity and environmental performance.

Finally, for the proposed optimized design with a one-section lengthening, the CII can be estimated based on (Equation 8), where the theoretical reduction in $CO_2$ emissions from the dual LNG-fuel system corresponds to the numerator, while the theoretical increase in DWT due to the lengthening is in the denominator. Under this relationship, a decrease in emissions and an increase in cargo capacity would result in a lower CII value. This comparison was conducted considering the same maritime route for both the original ship and the optimized design.

## Natural Frequencies and possible resonances of the Midship's Web Frame at Midship

The frequencies associated with the proposed dual-fuel engine were calculated, considering its operational range, and the natural frequencies of the web frame were estimated using POSEIDON. These data were used to generate the Campbell diagram and identify critical resonance panels.

**Table 13. Frequencies calculated.**

| Description | [Hz] |
|---|---|
| Ignition frequency | 36 |
| Ignition frequency * 1,2 | 43,2 |
| Propeller blade frequency | 9,65 |
| Propeller blade frequency * 1,2 | 11,58 |

Between the proposed 6-cylinder LNG-diesel dual engine, the gearbox with a ratio of 4.9725:1, and the 4-blade propeller, no significant risk of resonance was identified, as the excitation frequencies generated by these components are not multiples of each other. Since there are no harmonic coincidences among the engine cylinders, the gearbox, and the propeller blades, resonance issues were not observed in the propulsion system.

**Table 14. Frequencies in shell panel and in main deck.**

| Shell Panel | [Hz] | Main Deck | [Hz] |
|---|---|---|---|
| f1SP | 25,8 | f1D | 13,4 |
| f2SP | 9,4 | f2D | 73,3 |
| f3SP | 47,9 | f3D | 24,9 |
| f4SP | 10,0 | f4D | 31,1 |
| f5SP | 12,0 | f5D | 72,2 |
| f6SP | 46,1 | f6D | 66,2 |
| f7SP | 12,1 | f7D | 30,8 |
| f8SP | 49,8 | f8D | 83,1 |
| f9SP | 14,4 | f9D | 31,2 |
| f10SP | 14,9 | f10D | 183,6 |
| f11SP | 270,2 | f11D | 174,4 |

However, the analysis performed with DNV POSEIDON estimated two natural frequencies, f4SP = 10 Hz and f5SP = 12 Hz (Table 13), located in the upper part of the double hull (Fig. 7), which are close to the critical zone of 9,66 CPS, indicating a potential structural resonance risk. In contrast, none of the natural frequencies of the main deck showed any issues.

Since resonance in the double hull could compromise the structural integrity and service life of the ship, it is necessary to assess mitigation strategies. Possible solutions include adjusting the structural stiffness in critical areas, incorporating damping

**Fig. 14. Campbell Diagram of Longitudinal Plates in the shell.**

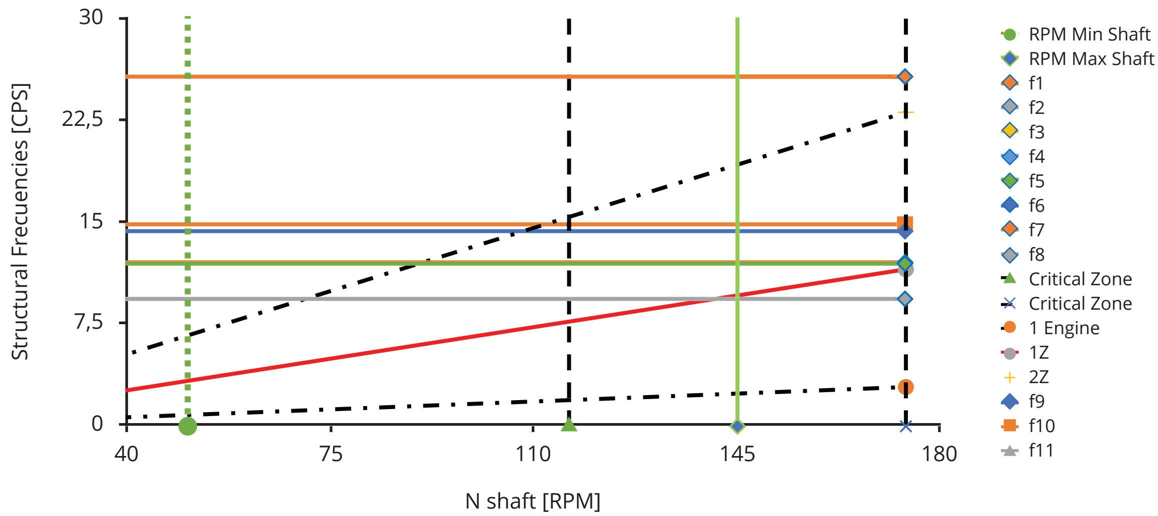
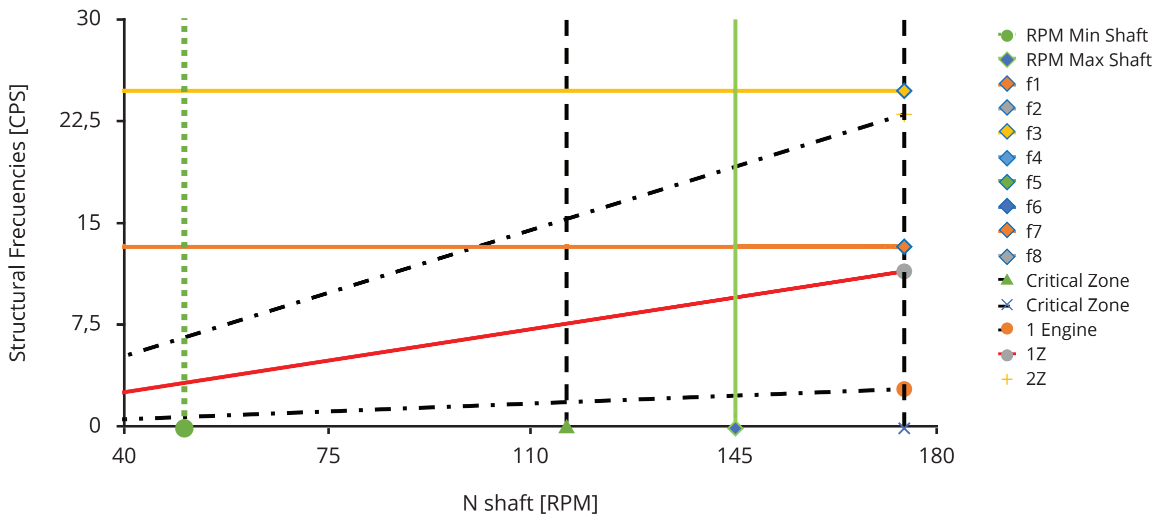



**Fig. 15. Campbell Diagram of Longitudinal Plates in the main deck.**




mechanisms, or modifying the reinforcement layout to shift the natural frequencies away from the critical zone. Additionally, it is recommended to conduct complementary experimental analysis to validate the numerical results and ensure the operational safety of the optimized ship.

## Conclusions and Recommendations

The sectional modulus for the lengthening of one section is close to the minimum required modulus indicated by classification societies, so analyzing an increase in depth could be considered for future studies.

Of the 22 natural frequencies estimated, only 2, corresponding to the shell panels, fall within the critical zone. If the system operation must occur within these critical zones, the vibration levels of the entire system should be evaluated to avoid operating at this RPM.

To mitigate resonances, the system stiffness can be increased by reinforcing the panels identified with this issue, so that natural frequencies shift due to design modifications, moving them away from excitation frequencies.

For a more precise vibrational analysis, the incorporation of additional web frames toward the aft section can be considered.

If you are interested in further discussion or exploring collaboration opportunities in Naval Engineering, please feel free to contact us.

## Footnotes

[1] ***Source: DNV Rules for Classification (2023), Part 3 Hull, Chapter 1.***
$f_R$: Operational profile factor, 0,85; $f_{nl-vh}$: Non-linear effects for hogging, 1; $f_m$: Distribution factor, 1, for 0,40 L ≤ x ≤ 0,65 L; $f_P = f_{PS}$ , 1, design load scenario; $C_W$ = 10,75 - (300 - L/100), for ships with a length between 90 and 300 m; $f_{nl-vh}$: Non-linear effects applied to sagging; = 0,5789*($C_B$+0,7/$C_B$).

[2] ***Source: ABS, Rules for Building and Classing, Marine Vessels, Part 3 Hull Construction and Equipment.***
$C_1 = 10{,}75 - (300 - L/100)^{1,5}$ ; $C_2$ = 0,01 ; $C_B$ = 1,0 - [0,195*(V/√$L_{PP}$)] , (CB is provided by the MaxSurf software for each proposed lengthening).

[3] ***Source: ClassNK, "Outlines of EEXI regulation". Nippon Kaiji Kyokai, August 2022.***
V = 10,50 [knots], speed developed by the original engine for the original tanker ship.
DWT = 4.629 [ton], for the original tanker ship.

[4] ***Source: IRCLASS, Implementing Energy Efficiency Design Index (EEDI), Indian Register of Shipping.***
V = 10,73 [knots], speed developed for the proposed lengthening of one section.
DWT = 5.812 [ton], result of DWT for the proposed lengthening of one section.

[5] ***Source: International Maritime Organization (IMO), "Carbon Intensity Indicator: A port and terminal perspective", GreenVoyage2050, 2023.***
Anual $CO_2$ emisions, are reduced in the optimized design compared to the original design.
DWT = 5.812 [ton], result of DWT for the proposed lengthening of one section.
Distance sailed, is equivalent in the original design and the optimized design, for the respective comparison.

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