MMA168
Structural Design for Sustainability Comparison of Materials

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Introduction

The task is to investigate how the choice of material will impact the stiffness, strength and price of a ship. How the choice of material will impact the environment must also be taken into consideration.

1 Moment of inertia

First the moment of inertia needs to be calculated for the given mid-body cross section, this is because the load case is simplified to a pure bending moment of a freely supported beam. The cross section and given dimensions in the task can be found in figure(1) and table(1).

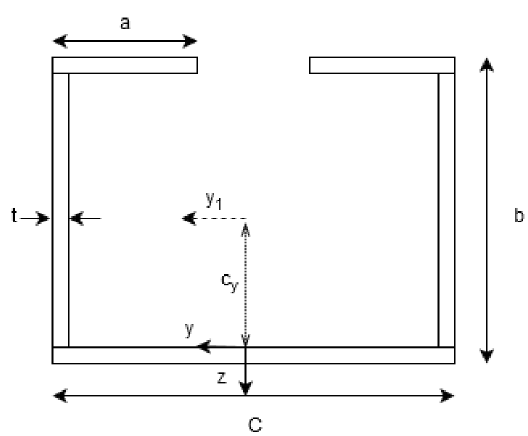

Figure 1: Mid-ship section

a	11.12 m
b	18.70 m
c	32.24 m

Table 1: Given measurements for the cross section

Material	Steel	Aluminum	GFRP
material density ρ, [kg/m^3]	7850	2700	1800
Young's modulus E, [GPa]	210	70	50
Yield stress σ, [MPa]	600	500	125
Material cost C_m, [USD/kg]	0.28	1.8	3
Hull thickness t, [m]	.16	.32	.4
safety factor against yield stress SF, [-]	7	12	3
CO_2 emission impact P_{co_2}, $\frac{g\ CO_2}{(tonnes\ km)}$ tonnes = weight of the ship km=ship route length	3	2.5	.75

Table 2: Material properties and other data related to material choice

All the material properties, price, yield stress and other important parameters to evaluate what material is best for the application and design can be found in table(2)

The first step to calculate the moment of inertia is to find the neutral axis, located in the center of gravity of the section. The easiest way of doing this is to first divide the section into multiple parts and multiply the area of each part with the distance from the Y-axis. This will be equal to the total area multiplied with the distance to the neutral axis. The step by step solution is shown in figure(2) and equation(1) to (3).

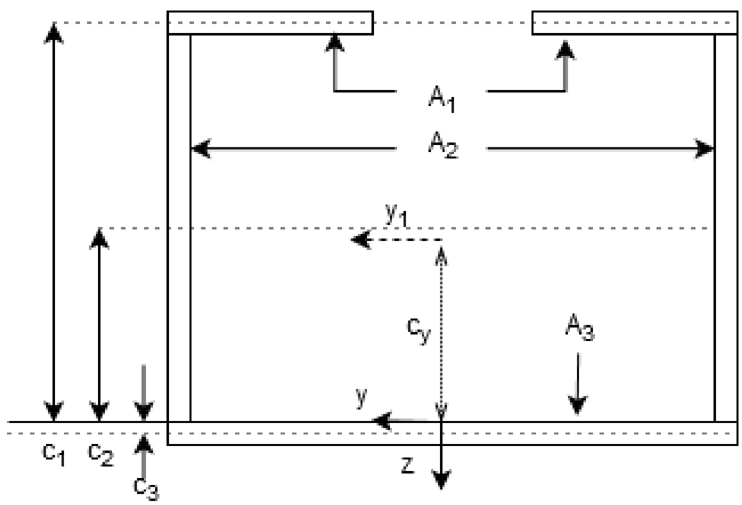

Figure 2: Areas in mid-ship section and distances for finding the neutral plane y_1

$$C_1 = b - \frac{3t}{2}, \quad C_2 = \frac{b}{2} - t, \quad C_3 = \frac{t}{2} \tag{1}$$

$$A_1 = 2at, \quad A_2 = 2(b - 2t)t, \quad A_3 = ct \tag{2}$$

$$C_y = \frac{\sum A_i \cdot C_i}{\sum A_i} \tag{3}$$

The result from the equations for the different materials is shown in table(3).

	Distance from y-axis to CG [m]			Area [m^2]		
Material	Steel	Aluminium	GFRP	Steel	Aluminium	GFRP
1	18,46	18,20	18,10	3,56	5,88	5,16
2	9,19	9,03	8,95	7,12	11,56	10,32
3	0,08	0,16	0,20	8,90	14,32	12,90

Table 3: Distances and areas for different materials

Now that the distance from the Y-axis to the neutral layer is established its possible to calculate the moment of inertia with the help of *Steiner theorem* or some times referred to as *parallel axis theorem* according to equation(6). For these calculations's to be carried out the distance from the local center of gravity to the neutral axis needs to be defined see figure(3), and the local moment of inertia. This is done in equation(4) and (5).

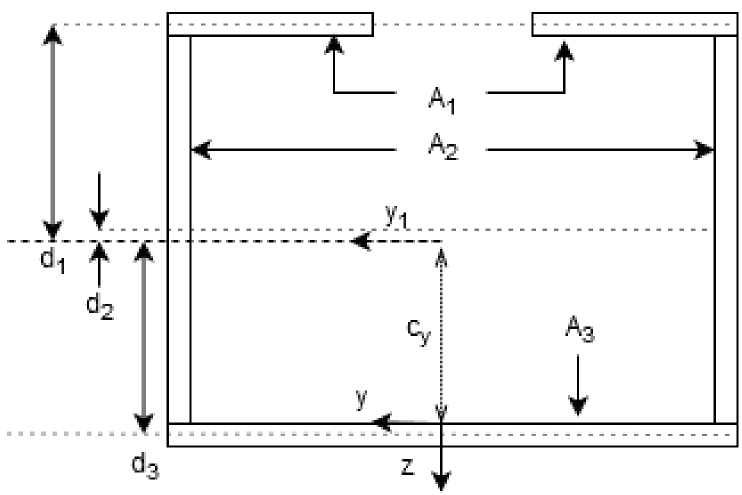

Figure 3: Areas in mid-ship section and distances for the local CG of the different components to the neutral plane

$$I_1 = \frac{2at^3}{12}, \quad I_2 = \frac{2t(b-2t)^3}{12}, \quad I_3 = \frac{ct^3}{12} \tag{4}$$

$$d_1 = C_1 - C_y, \quad d_2 = C_2 - C_y, \quad d_3 = C_3 + C_y \tag{5}$$

$$I_{c_y} = \sum I_i + A_i d_i^2 \tag{6}$$

The results from equation(4) to (6) is represented in table(4).

	Distance from y_1-axis to CG [m]			**Moment of inertia** [m^4]		
Material	Steel	Aluminium	GFRP	Steel	Aluminium	GFRP
1	10,29	10,20	10,16	899,6	1756,9	2170
2	1,02	1,01	1,01	*N/A*	*N/A*	*N/A*
3	8,25	8,18	8,13	*N/A*	*N/A*	*N/A*

Table 4: Distances from local center of gravity to the neutral axis Y_1 and moment of inertia

2 Deflection and normal bending stress

To investigate the maximum and minimum stress in the deck and keel equation(7), where n is a factor of 3 in this case, to simulate sea going conditions since the bending moment is calculated for calm water conditions, the equation was then plotted with the maximum and minimum allowed stress in the material with the safety factor in mind according to equation(8). The resulting plot is displayed in figure(4). Its worth to mention that the maximum and minimum allowed stress for aluminium and GFRP is the same because they have different safety factors.

$$\sigma_x(y) = \frac{n \; M_b \; y}{I_{y_1}} \tag{7}$$

$$\frac{\sigma_s}{SF} \tag{8}$$

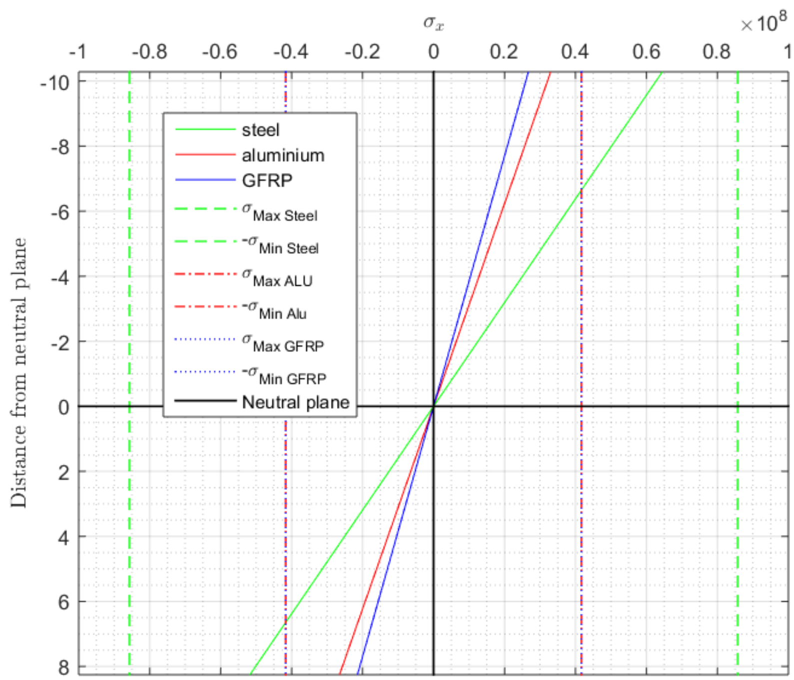

Figure 4: Maximum and minimum tension in the deck and keel with maximum and minimum allowed stress with the safety factor applied

Another important criteria for the design is the maximum deflection of the structure under load. To calculate the deflection equation(9) was used. In the same manner for the normal stress in the material the deflection was plotted over the length of the ship. See figure(5). It shouldn't come as a surprise that the maximum deflection occurs in the middle of the ship.

$$\Delta_x = \frac{n\ M_b\ L^2}{E\ I_y}\left(\frac{x}{L} - \left(\frac{x}{L}\right)^2\right) \tag{9}$$

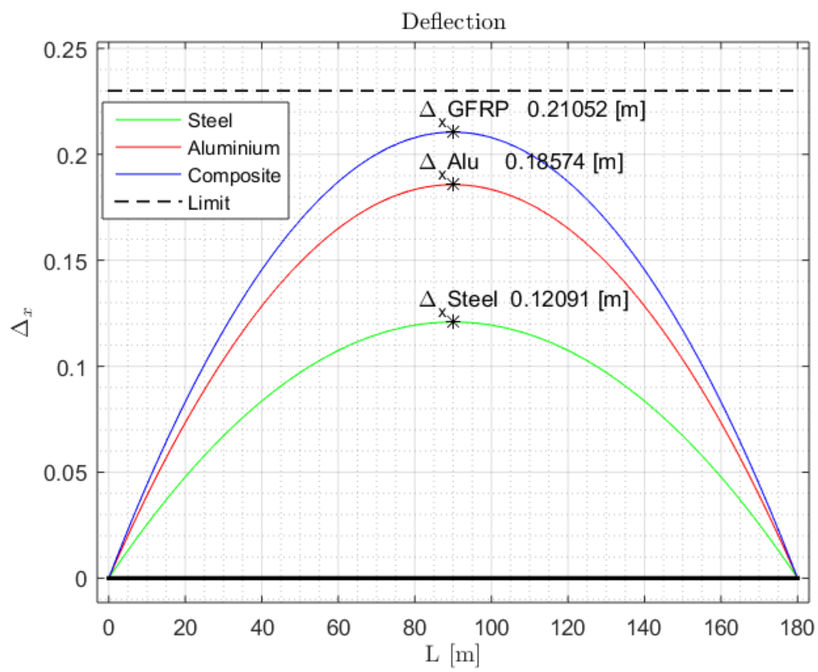

Figure 5: Deflection from the bending moment with the given thickness for the material

Its worth to mention that all of the materials are well within the specified boundaries and that the thickness of the hull can be reduced for the given load case, and thus decrease the cost and environmental impact of operation and building the ship.

3 Simplified LCA

From the available information initial data provided regarding the cost per Kg of three different materials, the cost per tonnes of CO_2 emission and the cost of single barrel of bunker oil; the material cost incurred for each material, the cost of CO_2 emission for each material and the cost of bunker oil required for each ship material is been separately estimated. The estimated price of each factors for the specific material is then been integrated and termed as the total cost which is represented in USD. Further to study the amount of influence of each factors on the total cost of a particular material, its been represented in terms of percentage for the ease of understanding as shown in table(5).

One can clearly observe from table(5) that a drastic shift from fuel cost to material cost will happen if the ship is built with aluminium or GFRP instead of steel. However these numbers are calculated with a service lifetime of 15 years. Steel is the cheapest material when compared to other two, so there is a break point when steel is cheaper than aluminium and GFRP respectively. This is illustrated in figure(7). In figure(6) the cost distribution is shown in a more graphical manner with the help of a pie chart.

Material	Material Cost	CO_2 *Cost*	Fuel Cost	Total Cost
Steel	4.7 %	4.2%	91.1%	$9.29 * 10^7$ USD
Aluminum	24.3%	2.8%	72.9%	$8.39 * 10^7$ USD
GFRP	35.4%	0.7%	63.9%	$9.04 * 10^7$ USD

Table 5: Table showing cost over life for the initial conditions

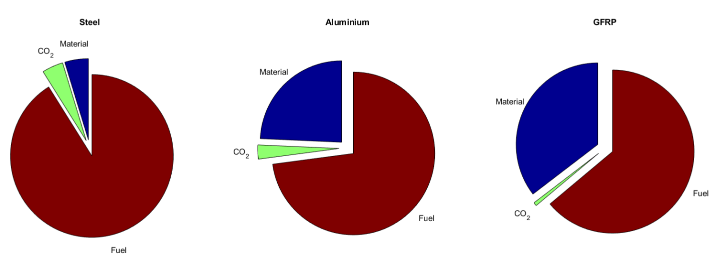

Figure 6: Figure showing cost over life for the initial conditions

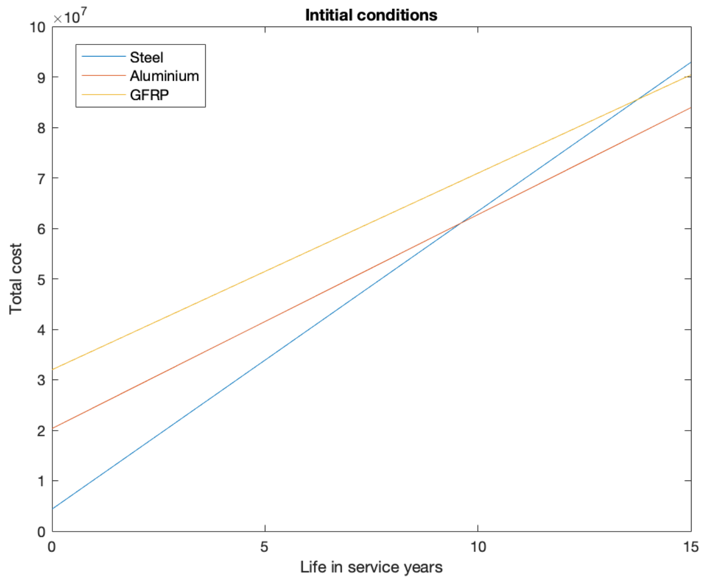

Figure 7: Figure showing Total cost over life for the initial conditions

Since the graphical way of representation is more easier to understand, the Total cost from the above shown estimation is plotted against the Service life of the ship(15 years). Hence looking at the resulting plot from figure (7), it seems that on a long run even though the material cost of the Steel being comparatively lesser than the other two, the total cost of the Steel gradually overtakes the Aluminium after aprrox. 10 years and the GFRP after aprrox. 14 years.

Therefore it's clear that unless and until proper estimation of the total cost over a certain period of time for a particular material isn't done, one cannot simply rely upon the rule of thumb in deciding the material for the ship just by looking at the material cost. But when it comes to the point of justifying the cost in a decision process of ordering a new ship, there are several factors we need to put some light on.

From the commercial point of view, our main priority is to reduce the cost incurring on the ship on various aspects. Hence first and foremost we will be investigating the expected service life of the ship, if the expected service life of the buyer is less than 10 years then according to the estimation made above its reasonable to opt for a steel hull ship. Else choosing between the other two according to the service life to minimise the cost.

From the sustainability point of view buyer is more concerned about CO_2 emission rather than the total cost. Hence in this case, comparing the CO_2 emission cost, it's clearly understood that GFRP has a very less cost influencing it's total cost which means that GFRP emits less CO_2 compared to the other two materials burning less amount of fuel; which could be a better option for a sustainable future.

The initial plot pictured above will be used as a reference for the comparison of all the cases we investigate in the next section.

4 Sensitivity analyses

By knowing the fact that the parameters we used in the estimation of the total cost of each material over a service life of 15 years of the ship doesn't remain constant over such a long period of time rather be variable. Hence it seems wise to investigate the total cost by varying the parameters now considered as variables by an assumed factors and check how sensible is its influence on the previous result by varying them. Therefore the parameters used earlier is being both increased and decreased by an assumed factor and then the resulting plot is compared with the considered reference plot in the previous section.

Initially for decreasing the material cost, the investigation is been done by decreasing the thickness by 10mm, 20mm and 30mm. The resulting plot is being shown in figure(8), (9) and (10).

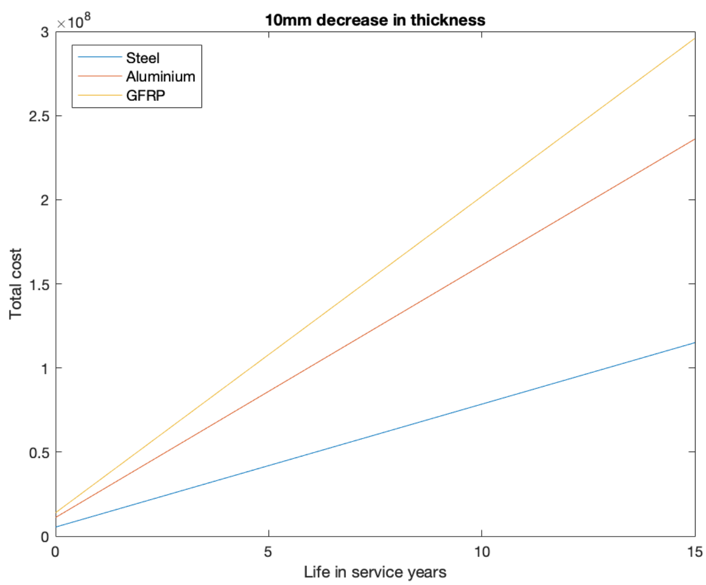

Figure 8: Figure showing cost over life with a 10mm decrease in thickness

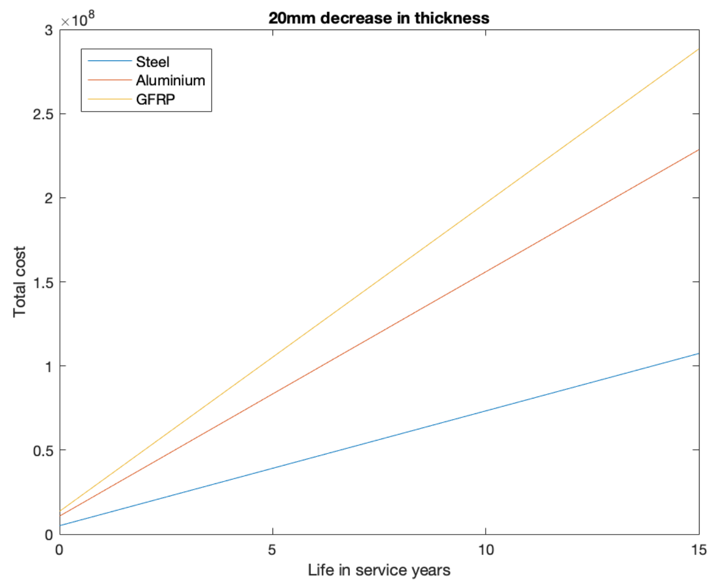

Figure 9: Figure showing cost over life with a $20mm$ decrease in thickness

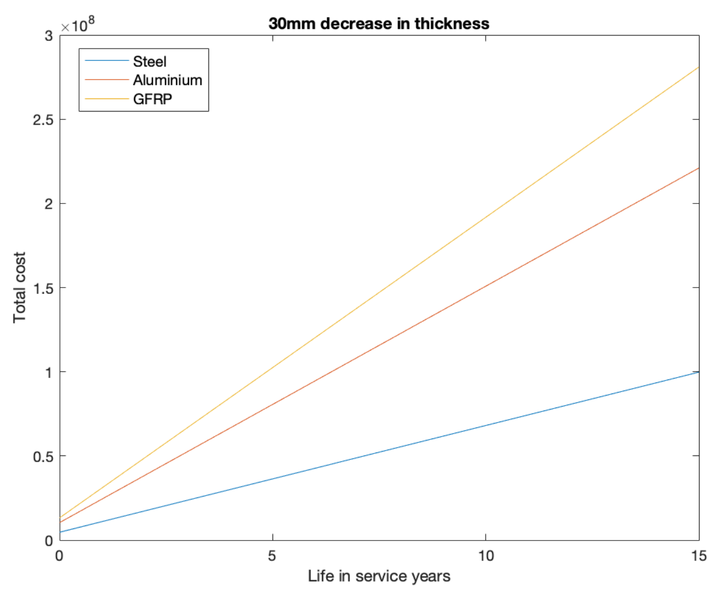

Figure 10: Figure showing cost over life with a $30mm$ decrease in thickness

To check that the hull is still stiff and strong enough, the same calculations and plots as done in section (2) was carried out. The resulting plots are shown in figure(11) and (12). Here the reader can see that the deflection for GFRP is close to design limit but does not exceed specified value. For stresses, steel hull is the one that is closest to the limit, however, its still below the specified limit and thus a functional design.

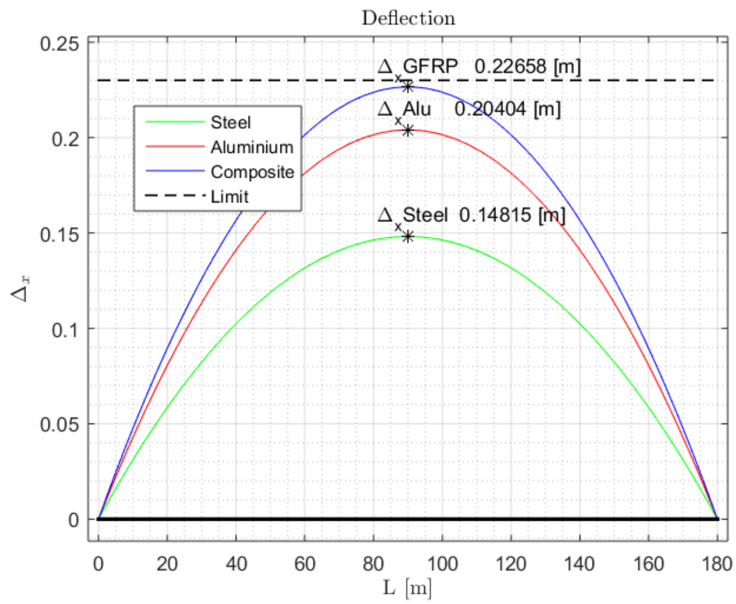

Figure 11: Stress with 30mm decrease in thickness

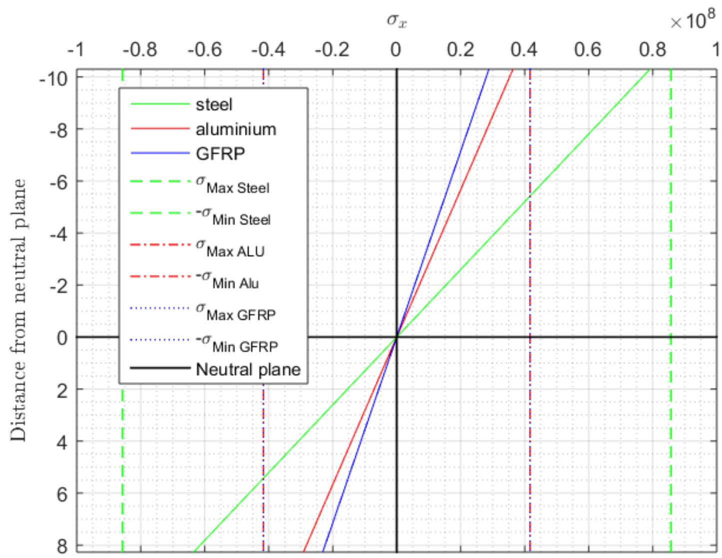

Figure 12: Deflection with 30mm decrease in thickness

The thickness is changed equally in mm for all the ships which creates a skewed view of the costs since aluminium ship is much further from the limiting conditions than steel and composite ships at a $30mm$ decrease. A more fair way of comparing would be to change the thickness as a percentage of allowed thickness. However if you just look at the same thickness decrease for each material, steel is the most preferable option for the materials at hand (if looking at the cost).

Secondly, the main topic of discussion in this present world is Carbon emission. It is taken as a variable for the investigation. Since the awareness regarding carbon emission is been increasing day by day its more likely to say that carbon emission cost will not decrease in future. Still for the sake of an organized investigation even carbon emission cost is being investigated for both increased and a decreased factor. The resulting plot is being shown in figure(13), (14) and (15).

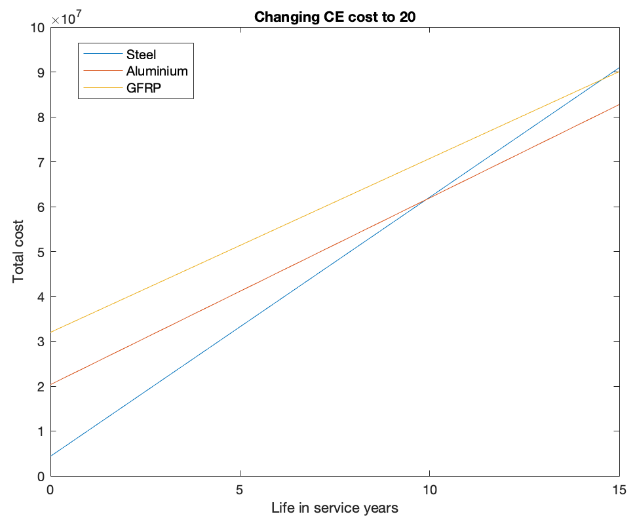

Figure 13: Figure showing cost over life with a factor 0.5 decrease in Cost of CO2 emission

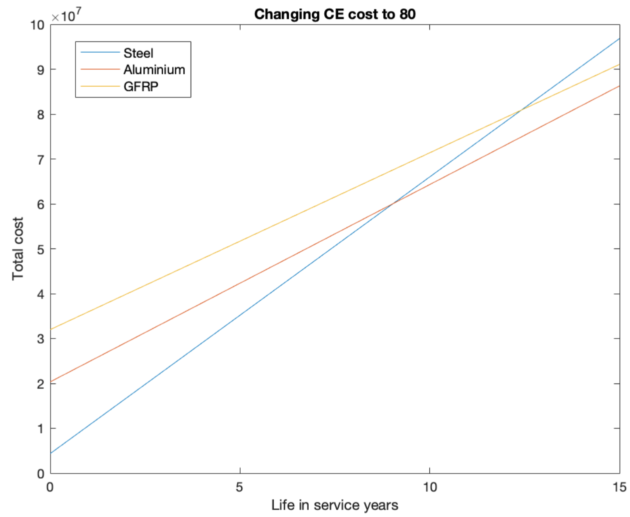

Figure 14: Figure showing cost over life with a factor 2 increase in Cost of CO2 emission

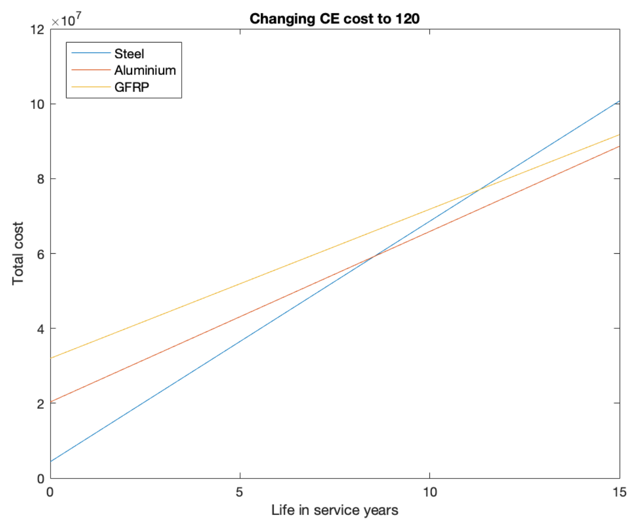

Figure 15: Figure showing cost over life with a factor 3 increase in Cost of CO2 emission

We can clearly understand from the plotted results that when carbon costs are increased, the benefits of a low production cost for the steel diminishes quicker than for the initial conditions. Hence from the sustainable point of view, steel won't fetch any profit as we move on with the years.

Thirdly, we decide to vary the price of oil which is being considered as the world's scarce resource. Even though it's more evident that the predicted price for the oil barrels is more likely to be increasing with the years, but one can see that there is recent trend of shift in the fuels and many shipping companies are thinking of shifting themselves to hybrid vessels for a sustainable future. Hence its better to investigate the result by varying oil price both by increasing and decreasing. The resulting plot is being shown in figure(16), (17) and (18).

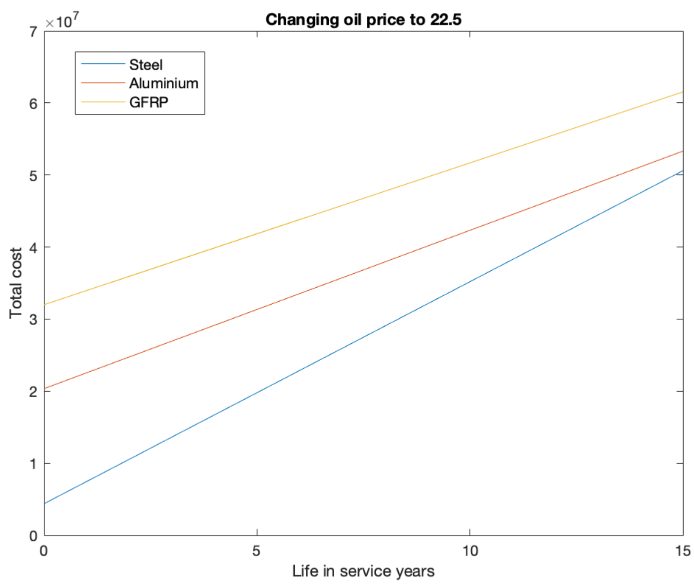

Figure 16: Figure showing cost over life with a factor 0.5 decrease in oil price

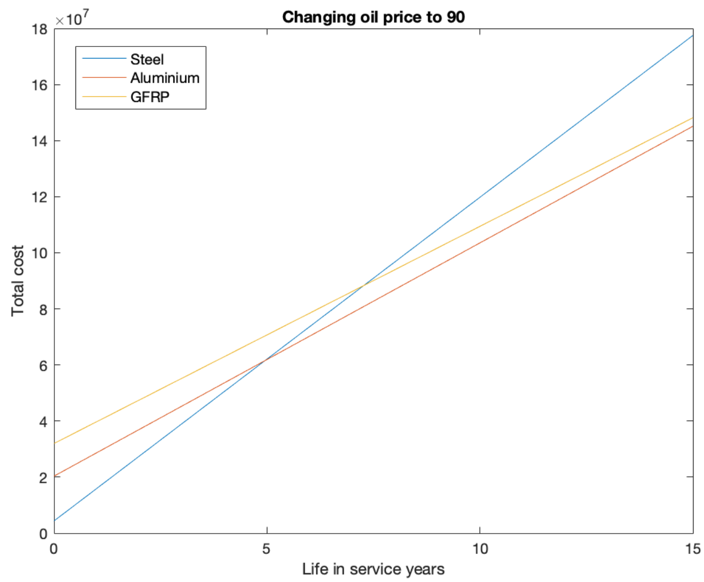

Figure 17: Figure showing cost over life with a factor 2 increase in oil price

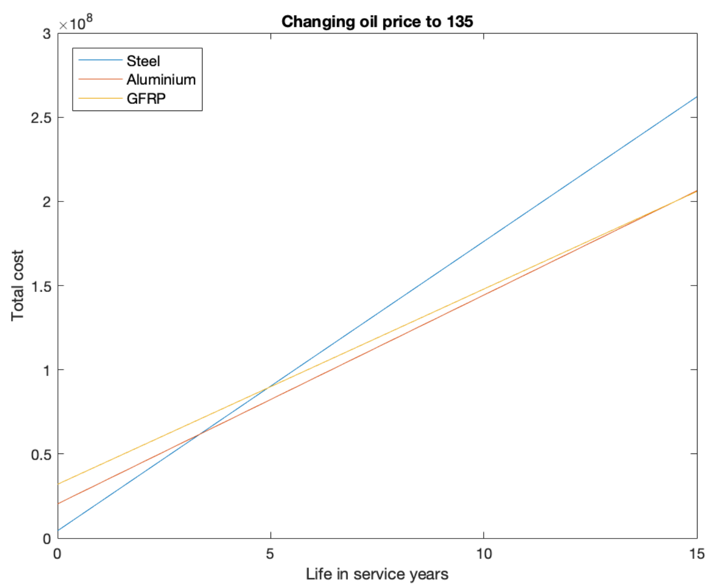

Figure 18: Figure showing cost over life with a factor 3 increase in oil price

The oil price is also varied to one lower point and two higher points. But in this case its crystal clear that the variation in oil price has a greater impact onto the total cost compared to all the other parameters. If oil prices were to be lowered, heavier steel ship would be advantageous. However, the more likely scenario of an increase in cost of a steel ship would quickly be unfavourable.

Lastly the remaining parameter which is more likely to change is the material cost; hence been considered to investigate its sensitivity towards the total cost over 15 years. The resulting plot is being shown in figure(19), (20) and (21).

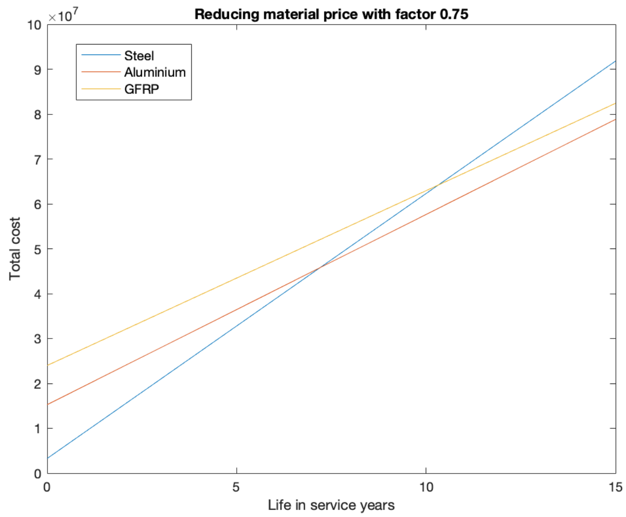

Figure 19: Figure showing cost over life with a factor 0.75 decrease in Material price

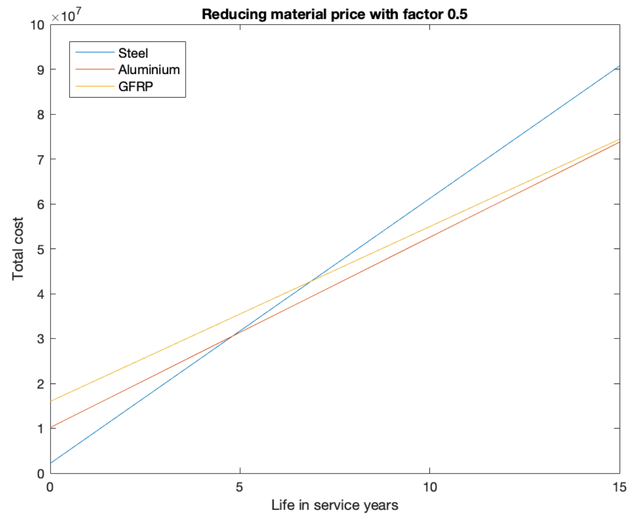

Figure 20: Figure showing cost over life with a factor 0.5 decrease in Material price

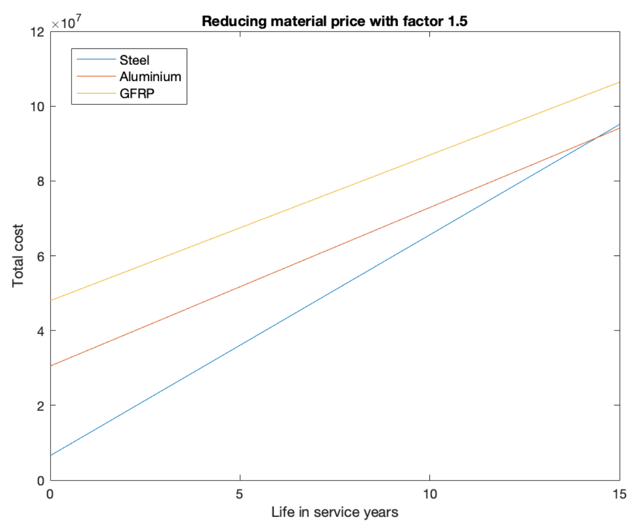

Figure 21: Figure showing cost over life with a factor 1.5 increase in Material price

The Material cost was also varied both up and down since the knowledge of future material market was insufficient and the prices vary cyclically with the market. A reduction in the material cost will be non-beneficial for steel ship since it already has a lower material cost compared to other ships. On the other hand if the material cost would increase, the lower mass price of the steel would benefit.