Project of a scissor lift platform and concept of an extendable cabin

Ricardo Duarte Cabrita
ricardo.ricab13@gmail.com

Instituto Superior Técnico, Lisbon, Portugal

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Abstract
This report presents the project of a lift platform coupled with a cabin (extendable up to 1 meter in its width) in the top of it, together with the company SEMECA,LDA.
The main goals of this report are: (1) lift platform and cabin development using Solidworks; (2) Material selection and design of all the elements that compose the lift; (3) Linking elements selection; (4) cost of production analysis.
Regarding the design of composing elements of the platform, was calculated the magnitude of the applied forces in the structure when the lift is starting the upward movement, because this is the most critical one. This analysis was done based on the methods presented in the book Mechanical Engineering Design and on the norms presented in Eurocode 3.
It was performed a structural analysis of the platform elements, as well as of the union between them, namely welding.
The hydraulic system was designed in order to successfully lift the platform using the minimum force needed. All components were designed in agreement with their function.
In conclusion, it is presented, at the end of this report, a lift platform that fulfill all the project specification stipulated.

Key words: Lift platform, Extendable cabin, Structural project, Oil-hydraulic

1. Introduction
A scissor lift is used to move cargo vertically. Despite this, it is possible to move it horizontally, because the lift can be driven like an ordinary car. Usually, it is driven by the force applied of one or more hydraulic cylinders or using an electric motor. Additionally, the upper platform can be coupled with a cabin. This type of lift is known as scissor lift due to the fact that it is composed by two pairs of beams connected through their gravitational centers [1]. These pairs are held parallel due to the beams with stipulated dimensions. By incorporating a close cabin, users could have work equipment inside it, avoiding damage to the equipment. The figure 1 shows an example of a scissor lift platform.

Figure 1 – Example of a scissor lift platform, similar to the one projected here. [2]
The lift projected will have 3 scissor “pairs”. The lift is symmetric, so it will have 6 scissor “pairs” (for comparison, the lift in figure 1 has 4 “pairs”). It will be coupled with an extendable cabin. The cabin’s width is variable from 2.5 meters to 3.5 meters but its length is fixed in 5 meters. It is driven by the force applied of two hydraulic cylinders, part of the hydraulic system. This system is responsible for the ascent and descent movement of the lift.

2. Project specifications
2.1 Project requisites
1) The platform should support 4000kg. This value already includes the weight of the cabin and the cargo/users.
2) The platform should go down completely and reach 6 meters in height.
3) The cabin’s width must be, at most, 2.5 meters when closed.
4) It should be used normalized components.
5) The cabin should have 1.8 meters in height.
6) The cabin should be extendable, in width, from 2.5 up to 3.5 meters.
7) The lift should have manual controls to control the ascent and descent of the lift and to open and close the cabin.
8) The cabin should have a stop system when it reaches 6 meters and the bottom.
9) The lift should be projected based on norms and codes in force.

2.2 Project constrains
1) The costs of productions and assembling the lift should be lower than 12 000 €.
2) It should be used materials that SEMECA, LDA is familiarized.
3) It should be used processes that SEMECA, LDA is familiarized (like MIG welding).

3. Norms and legislation
The lift platform is a structure mostly composed by steel, and, due to that fact it should be in accordance with the norms and legislation of the European Union, so that, at the end, it can be assumed that is safe to produce and use that same system. It will be used the norm NP EN 1993 – Eurocode 3: Design of steel structures [3]. To the structural steel, Eurocode 3 define the following material properties:

- Modulus of elasticity \( E = 210 \, \text{GPa} \)
- Poisson’s ratio \( \nu = 0.3 \)
- Shear Modulus \( G = \frac{E}{2(1+\nu)} = 81 \, \text{GPa} \)

3.1 Stress calculation in transversal sections of structural elements
To calculate the equivalent stress in a transversal section of a component, Eurocode 3 states that can be used the equivalent stress of von Mises, given by:

\[
\sigma_{V,M} = \sqrt{\sigma^2 + 3\tau^2}
\]

Note: \( \sigma \) represents the resultant of normal stress applied in that section and \( \tau \) represents the resultant of shear stress applied in that section. [3]

3.2 Stress calculation in welded joints
Regarding welded joints, it will be used the method presented in the book Mechanical Engineering Design. [4]

3.2.1 Stress in Welded Joints in Torsion
In the figure 2, it is represented a beam supported by two fillet welds. At the end of the beam it is applied a force \( F \). This force will create two different types of stress in the weld: a primary shear and secondary shear or torsion.

The primary shear in the welds is given by:

\[
\tau' = \frac{V}{A}
\]

where \( A \) represents the throat area of all the welds and \( V \) is the shear force. The secondary shear in the welds is given by:
\[ \tau'' = \frac{Mr}{J} \]

where \( r \) is the distance from the centroid of the weld group to the point in the weld of interest (critical point), \( J \) is the second polar moment of area of the weld group and \( M \) is the torsion moment.

The width of the welds are going to be considered equal to 1, being treated like lines and not like areas. The advantage of treating the weld size as a line is that the value of \( J_U \) is the same regardless of the weld size. As the width of a fillet weld is 0.707h, \( J \) can be related to \( J_U \):

\[ J = 0.707hJ_U \]

4. Methodology
The project was divided in 5 parts:
1. Lift platform modeling and structural project
2. Hydraulic system project
3. Lift platform assembling
4. Cost estimation to perform the 3 previous points
5. Extendable cabin modeling and function

4.1 Lift final structure
The solution found for the lift structure is presented in the figure 4. In the same figure is indicated the structure most important parts.

Characteristics:
- Weight (without cabin nor cargo): 3500 kg
- Width: 2.5 meters
- Length: 9 meters
- Height that the superior platform should reach: 6 meters
- Maximum allowed weight (cabin + cargo/users): 4000 kg
- The beams that form the “scissors” are joined by pins. Each beam has 3
connections (one in each extremity and one in the center)

Superior platform characteristics:
- Maximum width: 2.5 meters
- Maximum length: 5 meters

4.2 Extendable cabin structure
The solution found for the extendable cabin is presented in the figures 5 and 6. As stated before, this cabin can change its width from 2.5 up to 3.5 meters.

Cabin characteristics:
- Weight: 2300 kg
- Variable width: 2.5 up to 3.5 meters
- Length: 5 meters
- Walls move due to a rack-and-pinion system placed below the cabin.
- The superior part of the walls have an inclination of 45° and the inferior part is vertical.
- One of the fixed walls will have a door.

4.3 Hydraulic system
The hydraulic system (figure 7) will be responsible for:

1. Lift the platform up to the required height (6 m), through the hydraulic system and lower it in a controlled way.
2. Control the telescopic cylinders in order to fix the lift to the ground.

4.4 Total costs

4.4.1 Labor Costs
It will be necessary the work of 2 employees for 2 months to produce and assemble the lift. Approximately, it is 368 man-hours. The cost of each man-hour is 7€, so it sums up in 5152 €.

4.4.2 Material costs
Due to the fact that almost every part of the structure is composed by steel, it will be assumed as if all structure were composed by steel. Steel's price is around 1 € per kg (actually it is less, but it will be considered this price because not all the parts are composed by steel). The total material cost is approximately 3500 €. In welding consumable and gas it will be spent approximately 300 €.

4.4.3 Hydraulic system costs
In the figure 7, it is represented the hydraulic system, containing all its components. The total cost of the hydraulic system components is 1639 €, without considering the hydraulic cylinders because they were considered in the material costs.

4.4.4 Total costs
Having into account the costs presented previously come to a final value of 10591 € like its presented in the table 1.

<table>
<thead>
<tr>
<th></th>
<th>Valor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor</td>
<td>5152 €</td>
</tr>
<tr>
<td>Material</td>
<td>3 500 €</td>
</tr>
<tr>
<td>Welding consumable</td>
<td>300 €</td>
</tr>
<tr>
<td>Hydraulic system</td>
<td>1639 €</td>
</tr>
<tr>
<td>Total</td>
<td>10 591 €</td>
</tr>
</tbody>
</table>

Table 1 - Total costs
5. Structural design

5.1 Lift platform elements

In the figures 8, 9, 10 and 11 are represented the lift most important elements.
In the table 2 is represented the materials that compose each element and the corresponding yield strength.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Material (steel)</th>
<th>Yield strength ($\sigma_y$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>S235JR</td>
<td>235</td>
</tr>
<tr>
<td>3</td>
<td>S235JR</td>
<td>235</td>
</tr>
<tr>
<td>4</td>
<td>S235JR</td>
<td>235</td>
</tr>
<tr>
<td>5,6,7,8</td>
<td>S 235 JR</td>
<td>235</td>
</tr>
<tr>
<td>9,10</td>
<td>S 235 JR</td>
<td>235</td>
</tr>
<tr>
<td>11</td>
<td>S 235 JR</td>
<td>235</td>
</tr>
<tr>
<td>1,17,19,21,22</td>
<td>ck45 (hardened and tempered)</td>
<td>370</td>
</tr>
<tr>
<td>12,18,20</td>
<td>AISI 4320H</td>
<td>515</td>
</tr>
<tr>
<td>13,14,15,16</td>
<td>S 235 JR</td>
<td>235</td>
</tr>
</tbody>
</table>

Table 2 - Elements’ material and its yield strength. [5] [6] [7]

5.2 Loadings and simplifications
The lift has the function of, not only support the cabin and cargo’s weight but also elevate it from the bottom up to 6 meters. The cabin will be under different forces with different orientations. The maximum projected weight that the platform should lift is 5000 kg, where it is already applied a safety factor of 1.25. In other words, the maximum allowed weight, in use, is 4000 kg, comprehending the cabin and cargo.

5.3 Applied forces calculation
In this section, it will be studied the amount of stress that elements are under when the hydraulic cylinders are at the minimum slope (in the beginning of the ascent). This is the most critical moment because the vertical force applied by the hydraulic cylinders is very low due to the low slope. Consequently, the cylinders will have to apply a high amount of force.

Weight distribution in the superior platform may not be always uniform. However, this difference should not be significant because the users will be previously warned to avoid place a big weight in a small area. In the figure 12 it is represented the distributed load that is going to be considered.

![Figure 12 – Distributed load](image)

5.3.1 Forces applied in Element 1
In order to perform the structural analysis, it will be firstly estimated the force that the hydraulic cylinders will have to apply to lift the platform. It will be considered an equal distributed point through 4 support points in the superior platform. The total load is 5000 kg, as stated before and, consequently, the load applied in each point is 1250 kg. This force is represented as $W$. It will be calculated the forces applied in elements 1 and 2 because are these elements that are the most critical ones. In the figure 13 are represented the forces applied in the element 1. $F_m$ is the force applied by the hydraulic cylinder, $F_{my}$ and $F_{mx}$ are the components of $F_m$. $R_y$ and $R_x$ are the reactions due to connections with other elements. $\theta_m$ is the slope the cylinders make with the horizontal.

![Figure 13 – Applied forces in the Element 1](image)
5.3.2 Forces applied in Element 2

Element 2 is the beam that is connected through their centers (point E) with the element 1. The forces Fx and Fy are the forces that the element 1 apply in element 2 and vice-versa. θ is the slope the element 2 makes with the horizontal.

![Figure 14 - Applied forces in the element 2](image)

Based on the forces applied in the elements 1 and two, were defined 6 static equations. However, existed 7 variables: (Fx, Fy, Ry1, Rx1, Ry2, Rx2 e Fm), which leaded to undetermined equations. In order to calculate the values of each variable, the value of Fm was varied until Ry2 was negative, which indicated the platform was moving upwards. The value of each variable was:

- \( F_m = 190066.4 \text{ N} \)
- \( F_x = 171768.4 \text{ N} \)
- \( F_y = 20477.05 \text{ N} \)
- \( R_{x1} = 171768.4 \text{ N} \)
- \( R_{y1} = 8214.554 \text{ N} \)
- \( R_{x2} = 15311.71 \text{ N} \)
- \( R_{y2} = -820.347 \text{ N} \)

Each cylinder has to apply a total force of 190066.4 N, around 19 tons of force. The cylinders will have to apply this amount of force, only, in the moment when the lift is starting its ascent because it is, in that moment, that the cylinders have the lower slope.

5.4 Resistance analysis of elements 1 and 12

After determine the values of each applied force in the elements 1 and 2 it is necessary to do an analysis regarding the resistance each element. In this paper it is going to be studied the two most critical elements of the lift, element 1 and 12.

Each element will be analyzed based on the Eurocode 3. This code states the von Mises stress has to be smaller than its yield strength in every point of the element:

\[
\sigma_{V,M} = \sqrt{\sigma^2 + 3(\tau_x^2 + \tau_y^2)} < \sigma_y
\]

where:

\[
\sigma = \sqrt{\sigma_M^2 + \sigma_N^2}
\]

5.4.1 Element 1

In the figure 15 it is represented the section’s specifications and dimensions. In the figure 16 it is represented the free-body diagram regarding element 1.

![Figure 15 - Section specification and dimensions of element 1](image)

Each cylinder has to apply a total force of 190066.4 N, around 19 tons of force. The cylinders will have to apply this amount of force, only, in the moment when the lift is starting its ascent because it is, in that moment, that the cylinders have the lower slope.

![Figure 16 - Free-body diagram of element 1](image)
Can be verified by the free-body diagram that the section 2 is the critical one:

\[ V = 36777.3 \, N \]
\[ M = 41096.6 \, N.m \]
\[ N = -170949 \, N \]

Normal stress induced by the bending moment M:
\[ \sigma_M = \frac{M \cdot y}{I_{xx}} = \frac{41096.6 \times 0.1}{2444 \times 10^{-8}} \cong 168.15 \, MPa \]

Normal stress induced by normal load:
\[ \sigma_N = \frac{N}{A} = \frac{170949}{52.6 \times 10^{-4}} \cong 32.5 \, MPa \]

Due to the fact that this element is a slim beam, \( \frac{h}{l} = \frac{4.344}{0.2} = 21.73 > 10 \), the stress induced by the shear force (V) can be neglected. It is obtained the von Mises stress:
\[ \sigma_{VM} = \sqrt{\sigma_M^2 + \sigma_N^2} = \sqrt{(168.15 + 32.5)^2} \cong 200.65 \, MPa < 515 \, MPa \]

The von Mises stress is lower than the yield tension, so it can be assumed it is safe to use.

### 5.4.2 Element 12

In the figure 17 it is represented the section’s specifications and dimensions. In the figure 18 it is represented the free-body diagram regarding element 2.

The values for the variables in the figure X are the following:
\[ F = 190066.4 \, N \]
\[ l = 1.607 \, m \]
\[ a = 0.098 \, m \]

\[ \rho_1 = 45 \, mm \]
\[ \rho_2 = 55 \, mm \]
\[ l = \frac{1}{2}(R_2^4 - R_1^4) = 3.966 \times 10^{-6} \, m^4 \]

\[ R_1 = 45 \, mm \]
\[ R_2 = 55 \, mm \]

\[ I = \frac{\pi}{4} (R_2^4 - R_1^4) = 3.966 \times 10^{-6} \, m^4 \]

\[ 5.4.2 \text{ Element 12} \]

In the figure 17 it is represented the section’s specifications and dimensions. In the figure 18 it is represented the free-body diagram regarding element 2.

Can be verified by the free-body diagram that the section A is the critical one:
\[ V = 190066.4 \, N \]
\[ M = 18626.5 \, N.m \]

Normal stress induced by the bending moment M:
\[ \sigma_M = \frac{M \cdot y}{I_{xx}} = \frac{18626.5 \times 0.055}{3.966 \times 10^{-6}} \cong 258.31 \, MPa \]

Shear stress induced by the shear force (V):
\[ \tau_V = \frac{2V}{A} = \frac{2 \times 190066.4}{\pi(0.055^2 - 0.045^2)} \cong 121 \, MPa \]

The force is not applied in the centroid of the section, it is necessary to consider the stress induced by the torsion moment T. The moment is given by the multiplication of the distance between the centroid and the force, d, and the magnitude of the force, F:
\[ T = d \times F = 0.09 \times 190066.4 \]
\[ = 17105.98 \, N.m \]

Shear stress induced by the torsion moment T:
\[ \tau_T = \frac{T \rho}{J} = \frac{17105.98 \times 0.055}{\frac{\pi}{2} (0.055^4 - 0.045^4)} \cong 118.6 \, MPa \]

where J is the second polar moment of area
\[ J = \frac{\pi}{2} (R_2^4 - R_1^4) \]

The consequent von Mises stress:
\[ \sigma_{VM} = \sqrt{\sigma_M^2 + \frac{3}{2}(\sigma_V^2 + \sigma_T^2)} = \]
\[ = \sqrt{258.31^2 + 3 \times (121^2 + 118.6^2)} \approx \]
\[ \approx 390.95 \text{ MPa} < 515 \text{ MPa} \]

The von Mises stress is lower than the yield tension, so it can be assumed it is safe to use.

### 5.5 Resistance analysis of welded joints

SEMECA, LDA uses exclusively MIG welding. Therefore it were chosen two welding consumables: OK Autrod 12.50 and OK Autrod 12.63. The first is going to be used in every weld joint with exception of the weld that joins elements 12, 2 and 8, because OK Autrod 12.63 has a bigger yield tension, respectively 470 and 525 MPa.

#### 5.5.1 Welded joint between elements 12, 2 and 8

In this example it will be used an \( h = 6 \text{ mm} \), where \( h \) is the dimension of the throat. It is bigger than usually because this joint will be subject to the forces of the two hydraulic cylinders.

In the figure 19 it is represented the zone where it will placed the welded joint.

[Figure 19 - Welded joint characteristics and positioning]

The welded joint has the following characteristics:

- \( r = 0.055 \text{ m} \)
- \( d = 0.02831 \text{ m} \)
- \( F = 190066.4 \text{ N} \)
- \( T = Fd = 190066.4 \times 0.02831 \approx 5380.8 \text{ N.m} \)
- \( M = 18626.5 \text{ N.m} \)

\[
A = \frac{\pi}{4}hr = \frac{\pi}{4} \times 0.055 \times 0.006 \times 0.055
\]
\[ = 1.047 \times 10^{-3} \text{ m}^2 \]

\[
J_u = 2\pi r^3 = 2 \times \pi \times 0.055^3
\]
\[ = 1.045 \times 10^{-3} \text{ m}^3 \]

\[
J = 0.707 hf_u = 0.707 \times 0.06 \times 1.045\]
\[ \times 10^{-3} = 4.43 \times 10^{-6} \text{ m}^4 \]

\[
I_u = \pi r^3 = \pi \times 0.055^3 = 5.225 \times 10^{-4} \text{ m}^3 \]

\[
I = 0.707 hf_u = 0.707 \times h \times 5.225 \times 10^{-4}
\]
\[ = 2.217 \times 10^{-6} \text{ m}^4 \]

Stresses that the welded is subject to:

\[
\tau_V = \frac{F}{A} = \frac{190066.4}{1.047 \times 10^{-3}} \approx 129.656 \text{ MPa} \]

\[
\tau_T = \frac{Tr}{T} = \frac{5380.8 \times 0.055}{4.43 \times 10^{-6}} \approx 66.738 \text{ MPa} \]

\[
\tau_M = \frac{Mr}{T} = \frac{18626.5 \times 0.055}{2.217 \times 10^{-6}} \approx 462.046 \text{ MPa} \]

The critical point is the one where \( \tau_V \) and \( \tau_T \) are collinear. The total shear stress in that point is:

\[
\tau = \sqrt{\tau_V^2 + \tau_T^2} = \sqrt{(129.656 + 66.738)^2 + 462.046^2} = 502.053 \text{ MPa} < 515 \text{ MPa} \]

#### 5.6 Structural analysis using finite elements Element 12

The maximum von Mises stress verified using finite elements is 411.3 MPa. Previously, it was verified that, using the method in Eurocode 3, the maximum von Mises stress verified was 390.95 MPa. The figure 20 represent the magnitude of the von Mises stress in the element 12. The difference between the results obtained in both methods is:

\[
\%_{\text{diff}} = \frac{\sigma_{VM, (E.F.)} - \sigma_{VM, (Analytic)}}{\sigma_{VM, (E.F.)}} \times 100
\]

\[
= \frac{411.3 - 390.25}{411.3} = 0.051
\]

\[ \approx 5.1\% \]

[Figure 20 - Analysis of element 12 using finite elements]
6. Conclusions and future developments
This document presents the project of a lift platform requested by SEMECA, LDA. The structural analysis was done based on Eurocode 3 and the book Mechanical Engineering Design. It was studied the forces and stresses applied when the platform is starting its ascent. It was done an analysis regarding all the elements and their union, through welded joints. It was chosen materials with a yield stress higher than the von Mises stress they were subject to and at the same time the most economical possible. Element 12 is the most critical due to the fact that it is in direct contact with the hydraulic cylinders. The von Mises stress calculated using the method presented in Eurocode 3 and using the finite elements method differ 5.1%.
Additionally, it was made a concept of an extendable cabin as well as all the mechanisms that enable its movement. In the future, it should be done the structural analysis of the extendable cabin in order that this cabin can be manufactured too. It also should be done a study of the forces applied in the platform and cabin when this is subject to bad weather conditions (when the platform is in use, especially if the superior platform is at the higher height possible, 6 meters). An electric system should be designed to allow the user to easily rise and lower the lift as so as extend or retract the moving walls of the cabin. It can be optimized the position of the cylinders or even placing another one in order to decrease the load applied by each one. To sum up, all the objectives stipulated were fulfilled. In the end it was obtained a stable lift platform that support 4000 kg as so as the concept of an extendable cabin, as requested by SEMECA, LDA.

7. References
[3] NP EN 1993, Eurocode 3 – Project of steel structures (parts 1 and 8), March 2010