Finding the Optimal Shape of Hydraulic Scissors Lift Legs Using HHO Optimization Method

Marko Todorović[1*], Radovan Bulatović[1], Mile Savković[1], Goran Marković[1]
[1]Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, SERBIA

By analysing the forces in legs of the hydraulic scissors lift using symbolic variables, the expressions for stress have been derived. Novel Harris hawks optimization algorithm had been used in order to get the optimal values of variables that present geometrical characteristics of the cross section of the hydraulic scissors legs, for the given scissors lift. By connecting the optimal cross sections across the length of the scissors lift legs, optimal geometric shape of the scissors lift legs had been acquired, and displayed in this paper.

Keywords: Harris hawks optimization, hydraulic scissors lift, optimal shape of scissors lift legs

1. INTRODUCTION

Lifting platforms that employ the scissors mechanism are very commonly used in various situations where it is needed for load that contains objects, people, or both at the same time to be transferred across the vertical plane. They can be installed permanently in which case they cannot be easily moved to different locations without disassembling them. There are also mobile lifting platforms with scissors mechanism where the mechanism is installed on some kind of carts or trailers.

The mechanism itself is consisted of one pair of beams on each side that are connected in the middle, making one pair of scissors. Multiple pairs of scissors can be stacked on top of each other which enables the platform to be lifted to higher altitude with shorter beams.

Lifting is usually accomplished by hydraulic or pneumatic cylinders that are connected to the beams of the scissors mechanism, so the whole mechanism can be illustrated as presented in figure 1.

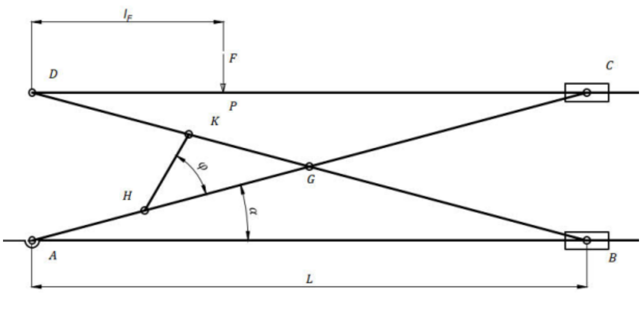


Figure 1: Ilustration of the lifting platform with scissors mechanism

By elongating the hydraulic or pneumatic cylinder, the angle between the beams changes which, as one end of each beam is fixed, leads to platform changing the altitude and load being lifted.

During the design process of any piece of machinery or mechanism, the goal is to achieve the best performance and stability, while lowering the amount of material used for construction. That is a good practice because, not only it makes the final product cheaper, but it makes it lighter which reduces the dead load, hence the energy needed for the mechanism to work is lower.

The dead load reduction can be accomplished by using the optimal geometrical shape of the beams, and the optimal shape can be derived using different optimization methods.

In papers [1] and [2] the kinetic analysis of hydraulic scissor lifts with a single set of scissors is being represented, while in the article [3] more general expressions were derived for lifting platforms with multiple sets of scissors stacked on each other. Using similar mathematical model, kinetic analysis will be done in such way that it can be used as starting point for the optimization algorithm.

Optimization represents a process where the most superior values of the parameters (variables) are obtained based on the given constraint functions, for the observed objective function. [4] There are many optimization methods that can be used for sucessfully completing this task. In past decades, many new p-metaheuristic methods have been developed, and one of them, the novel Harris Hawk optimization method that was purposed in the article [5], will be used for performing the optimization.

2. HARRIS HAWK OPTIMIZATION

Harrison hawk optimization, described in detail in the article [5] is metaheuristic, population based optimization method. Its creation is inspired by the specific ways Harris hawks hunt in groups.

Initial population in this method is consisted of randomly generated positions of hawks in set boundaries which represent hunting area. The best solution in each iteration represents the prey which escapes within the searching area. Based on prey’s energy, hawks change the way they attack the prey. Energy of the prey represents the value of the objective function for the values of parameters that are being stored inside of the prey’s location.

As the hawks hunt the prey, the location of the hawks evolves through the iterations until the set number of iterations has been completed following this rule:

$$X(t+1) = \begin{cases} X_{rand}(t) - r_1|X_{rand}(t) - 2r_2X(t)| & q \geq 0.5 \\ (X_{rabbit}(t) - X_m(t)) - r_3(LB + r_4(UB - LB)) & q < 0.5 \end{cases} \quad (1)$$

…where the $X_{rand}(t)$ represents location of random hawk in the previous iteration t, $X(t)$ represents the location of each hawk in iteration t, $X_{rabbit}(t)$ is the location of the prey in the iteration, LB and UB are limits of the searching area, q is the chance for hawks to choose each perching

*Corresponding author: Dositejeva 19, 36000 Kraljevo, Serbia, todorovic.m@mfkv.kg.ac.rs

strategy, and $X_m(t)$ is the average position of all hawks in the current iteration.

Energy of the prey is modelled in the way that it decreases through iterations, as the prey, mostly rabbit gets more and more tired as it is being chased by the hawks. If the value of the energy of the prey is less than 1, it means the rabbit is weak enough for hawks to attack it. This means that the optimization algorithm switches from the phase of exploration to the phase of exploitation. The energy of the prey is being calculated using the following rule:

$$E = 2E_0\left(1-\frac{t}{T}\right) \tag{2}$$

In the equation (2), E_0 is the number that randomly changes its value in the interval (-1,1), t is the number of the current iteration, while T is the total number of iterations. Different phases of the optimization process are being illustrated in the figure 2.

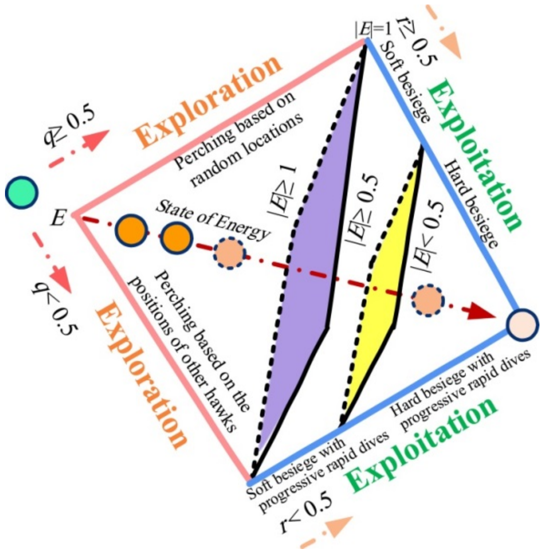


Figure 2: Different phases of Haris Hawks optimization algorithm [6]

The source code provided with the article [5] is consisted of four scripts written in MathWorks Matlab programming languages: *main.m, initialization.m, HHO.m, Get_Fuctions_details.m*.

The “*main.m*” script is the script where the number of members of initial population (number of hawks) is being defined, the name of the object function that is addressing the function with the exact name from the *“Get_Function_details.m”* file, as well as the total number of iterations the optimization algorithm is supposed to complete. This script is the script that starts the optimization process, and it calls all other scripts and functions.The first script that is being called is the *“Get_Function_details.m”* script which contains all the needed information about the object function: lower and upper boundaries of the searching area, the dimension of the problem, and it calculates the value of the object function. This is the file that is usually being modified for the purpose of performing custom optimization.

When the needed parameters are defined as output from the previous script, the script *“HHO.m”* is being called. Input for this script contains all of the previously defined variables: number of members of the initial population, total number of iterations, limits of the searching area, as well as the value of the object function. This script first calls the *“initialization.m”* script which then creates the initial population following the rules defined in previous steps, after which the optimization process begins. The initial population evolves through iterations until the maximum number of iterations is completed. The outputs from the *“HHO.m”* are the *“Rabbit_Location”* (optimal values of the optimized variables) and the *“Rabbit_Energy”* (value of the object function for the values of optimized variables). Illustration of the algorithm is shown in the figure 3.

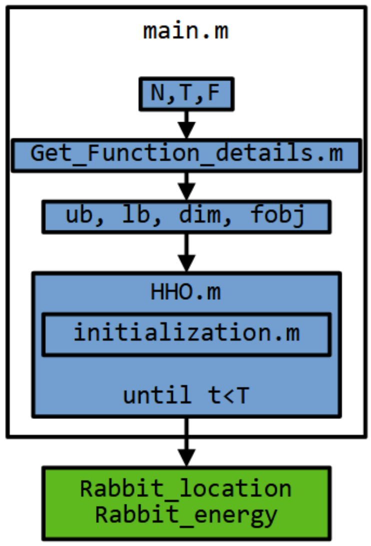


Figure 3: Illustration of the source code of the HHO algorithm: N – number of hawks, T – total number of iterations, F – name of the function, ub, lb – boundaries of the searching interval, dim – dimension of the problem, fobj – value of the object function, t - current iteration

3. KINETIC ANALYSES

In order to perform the optimization, it is required to define the object function as well as the constraints, which is why it is necessary to perform kinetic analyses. Since these platforms usually carry the load that often can be humans, the speed of lifting is usually not high, so dynamic changes of load in the components of the platform can be neglected, therefor the platform can be observed as static structure.

The structure of the platform is consisted of two legs of equal length, AC and AB, hydraulic cylinder GH that is usually placed in the plain behind the mechanism itself, but for the purpose of performing the kinetic analyses it can be represented as shown in the figure 1. Cylinder is connected to the leg AB over pin support G which is placed on a distance *a* from the pin E, and it is connected to the leg BD over the pin H that is placed on a distance *b* from the pin G, forming the triangle GEH. The ends of the legs, A and D are fixed with pin supports, while B and C are connected to pinned collar on smooth rod which enables them to move in horizontal direction as the platform is lifting or lowering. The angle between the leg AC and ground is labelled as the angle α, the angle EGH is labelled as the angle φ, while the angle GHE is labelled as the angle β. Since the pin E is located in the middle of both legs, the angle GEH equals 2α. On the horizontal metal sheet CD the load T is being placed on distance l_f from the pin C.

When disassembled, directions of the forces in the pins of individual components can be assumed as it is represented in the figure 4.

Based on the assumed directions of forces in figure 3, system of equations can be formed.

Static equations for the member DE:

$$\Sigma X_i = 0: X_D = 0 \tag{3}$$

$$\Sigma Y_i = 0: Y_D - T + Y_C = 0 \tag{4}$$

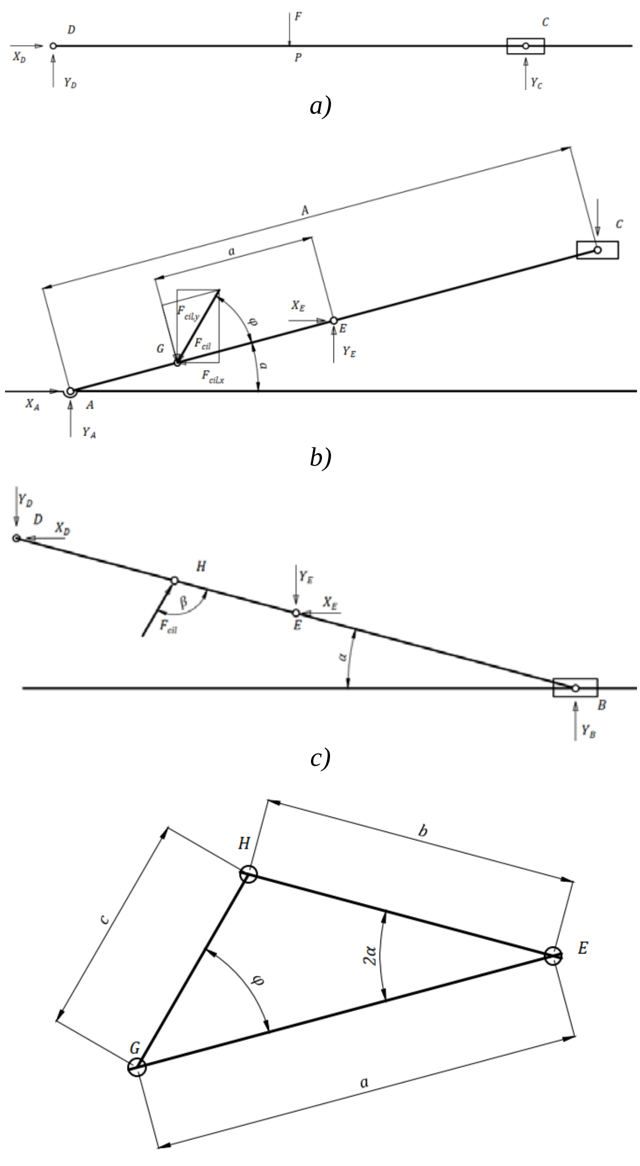
$$\Sigma M_{i(D)} = 0: Y_C L - T l_f = 0 \tag{5}$$

Static equations for the member AC:

$$\Sigma X_i = 0: X_A - F_{cil}\cos(\alpha+\varphi) + X_E = 0 \tag{6}$$

$$\Sigma Y_i = 0: Y_A - F_{cil}\sin(\alpha+\varphi) + Y_E - Y_C = 0 \tag{7}$$

$$\Sigma M_{i(E)} = 0: -\frac{Y_A L}{2} + F_{cil}\sin(\varphi)\,a - \frac{Y_C L}{2} + \frac{X_A \sin(\alpha)}{2} = 0 \tag{9}$$



a)

b)

c)

d)

Figure 4:Free body diagram of the lifting platform: a) horizontal metal sheet, b) leg AC, c) leg BD, d) triangle GEH

Static equations for the member BD:

$$\Sigma X_i = 0: -X_D + F_{cil}\cos(\alpha+\varphi) - X_E = 0 \tag{10}$$

$$\Sigma Y_i = 0: -Y_D + F_{cil}\sin(\alpha+\varphi) - Y_E + Y_B = 0 \tag{11}$$

$$\Sigma M_{i(E)} = 0: \frac{Y_B L}{2} + \frac{Y_D L}{2} - F_{cil}\sin(\beta)\,b + \frac{X_D A\sin(\alpha)}{2} = 0 \tag{12}$$

Solutions of this system of nine equations are:

$$F_{cil} = \frac{LT}{2a\sin(\varphi)} \tag{13}$$

$$Y_D = T - \frac{T l_f}{L} \tag{14}$$

$$Y_C = \frac{T l_f}{L} \tag{15}$$

$$X_E = F_{cil}\cos(\alpha+\varphi) \tag{16}$$

$$X_A = 0 \tag{17}$$

$$Y_A = \frac{2}{L}\left(F_{cil}\sin(\varphi)\,a - \frac{Y_C L}{2}\right) \tag{18}$$

$$Y_E = \frac{2LY_C + F_{cil}(\sin(\alpha+\varphi)\,L - 2a\sin(\varphi))}{L} \tag{19}$$

$$Y_B = \frac{L(Y_D + 2Y_C) - 2a\sin(\varphi)\,F_{cil}}{L} \tag{20}$$

…where L represents the horizontal projection of the length of the platform leg A, and F_{cil} is the force withing the hydraulic cylinder.

The mass of the scissors lift itself was not accounted in the previous system of equations because, as it is stated in the article [3], the weight of the scissors lift itself can be added to the active load:

$$T = Q\cdot g + \frac{m_p\cdot g}{2} = \frac{2Q + m_p}{2}\cdot g \tag{21}$$

For the purpose of this paper, the mass of the scissors lift will be neglected.

4. OBJECT FUNCTION AND CONSTRAINTS

It was assumed that for the scissors platform legs would be used a beam with the cross section that is shown in figure 5.

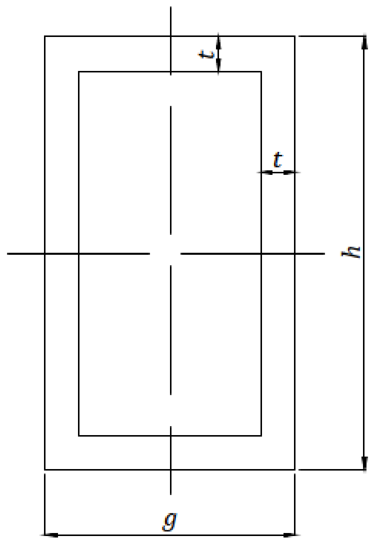


Figure 5: The cross section of the beam: t – thickness of the box, h – height of the box, g – width of the box

By knowing the shape of the cross section, the geometrical properties and the load in each point across the length of the legs, the diameter of pins A, B, C, D, E, G and H can be calculated. Considering that the attack force on the pins is making shear stress within it, the diameter of the minimal diameter of the pin can be determined in the following way:

$$d = \sqrt{\frac{4 \cdot F_s}{m \cdot \pi \cdot \tau_{dop}}}; d_0 = d + 0.1 \text{ (cm)} \tag{22}$$

…where d is the diameter of the pin, m is the number of shear surfaces, τ_{dop} is allowed shear stress in the pin for the given material, and F_s is the shear force that is attacking the pin, and it is equal to:

$$F_s = \sqrt{T(z)^2 + A(z)^2} \tag{23}$$

Putting the pins in the beam that makes a leg of the scissors lift platform weakens the beam, so the cross section at those places have the shape that is represented in figure 6.

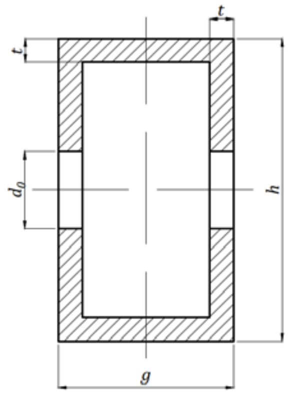


Figure 6: The weakend cross section of the beam

4.1. Object function

The goal of the optimization is to find the optimal ratio between the height and width of the cross section of the beam for the given static load. In order for that to be accomplished, the shear stress, normal stress and combined stress in the beam should not exceed the allowed values for the material from which the beam was made, but it should be close to that limit.

The minimal area of the cross section, or the minimal moment of inertia can be calculated, but the question that remains is if the cross section should have higher height or width, and by how much should one dimension be larger than the other. The optimization algorithm such as HHO can help in the search for the answer to the question.

Since the load of the beam changes along its length, the optimal height and width of the profile in the cross section changes accordingly. The thickness t, on the other hand, will be taken as constant in every point of the beams.

In order to perform the optimization, appropriate object function must be set within the code. Considering the expressions for calculating the shear τ and normal stress σ are:

$$\sigma(z) = \sigma_M(z) + \sigma_A(z) = \frac{M(z)}{I_x(z)} y_{max}(z) + \frac{A(z)}{S(z)} \tag{24}$$

$$\tau(z) = \frac{T(z) \cdot S_x(z)}{I_x(z) \cdot t} \tag{25}$$

…the combined stress can be calculated with the following expression:

$$\sigma_u(z) = \sqrt{\sigma(z)^2 + 3 \cdot \tau(z)^2} \tag{26}$$

…where the variables are:

- $\sigma_M(z), \sigma_A(z)$ – normal stress from the bending moment and axial force at the point z;
- $\tau(z)$ – shear stress from the shear force at the point z;
- $M(z), T(z), A(z)$ – bending moment, shear force and axial force at the point z;
- $S_x(z), I_x(z), S(z)$ – the first moment area, moment of inertia and area of cross section at the point z:

$$S_x(z) = g(z)t\frac{h(z) - t}{2} + t\left(\frac{h(z)}{2} - t\right)^2 - \frac{d_0(z)^2}{4}t \tag{27}$$

$$I_x(z) = 2 \cdot \left[\frac{g(z)t^3}{12} + g(z)t\left(\frac{h(z) - t}{2}\right)^2 + \frac{t(h(z) - 2t)}{12} - \frac{td_0(z)^3}{12}\right] \tag{28}$$

$$S(z) = 2t(g(z) + h(z) - 2t - d_0(z)) \tag{29}$$

Since the optimization algorithm searches for the optimal values of the variables in such way that the object function has minimal value, and the combined stress in this situation should as high as it is allowed, then the optimization algorithm has to minimize this function:

$$\sigma_u(z) = -\sqrt{\sigma(z)^2 + 3 \cdot \tau(z)^2}. \tag{30}$$

4.2. Limits of the searching area

The cross section of the beams has a shape of a box, as presented in the figure 5 and the figure 6. Considering that the thickness of the wall of the box is constant across the length of the beam, the only two variables are height and width of the box.

If either the height or the width of the cross section is equal to $2 \cdot t$, then the shape of the cross section is not a box, but rather a rectangle. In order to keep the shape of the cross section a box, the minimal height and width of the cross section of the beams should be $2 \cdot t$. The lower boundary in the script *"Get_function_details.m"* is defined as the vector, and it has the following form:

$$lb = [2 \cdot t, 2 \cdot t] \tag{31}$$

The maximum values of the height and the width are not as important. Lower upper boundary should result in faster convergence to the optimal solutions, but this should be taken with precaution, because it still has to be high enough so the possible optimal solutions would not be cut out by setting the upper limit too low.

4.3. Constrains

In order to get the shape of the structure that can safely endure the given load, normal stress, shear stress, as well as combined stress must not exceed the limits for the given material. Following that thought, the four limits can be set:

$$g_1 = \sqrt{\sigma(z)^2 + 3 \cdot \tau(z)^2} - \sigma_{dop} \leq 0; \tag{32}$$

$$g_2 = \frac{A(z)}{S(z)} - \sigma_{dop} \leq 0; \tag{33}$$

$$g_3 = \frac{M(z)}{I_x(z)} \cdot \frac{h(z)}{2} - \sigma_{dop} \leq 0; \tag{34}$$

$$g_4 = \frac{T(z)S_x(z)}{I_x(z)t} - \tau_{dop} \leq 0. \tag{35}$$

Additional two constraints can be applied so the width would not be too bigger then height, and the other way around. This behaviour can be constrained in the following way:

$$g_5 = \frac{g(z)}{h(z)} - 3 \leq 0; \tag{36}$$

$$g_6 = \frac{h(z)}{g(z)} - 3 \leq 0. \tag{37}$$

One additional constraint should be applied in the places where the pins pass through the beams:

$$g_7 = 4 \cdot d_0 - h \leq 0 \tag{38}$$

4.4. Source code modification

The optimal shape of the hydraulic scissors lift legs can be acquired by doing multiple optimizations across the length of the legs. Each of the legs has been divided into three sections and each section is divided into ten equidistant subsections, as it is shown in figure 7, where the optimization is performed for each of them individually. Hence, the leg AC has been divided into sections: AG, GE, EC, and the leg DB has been divided into sections: DH, HE and EB.

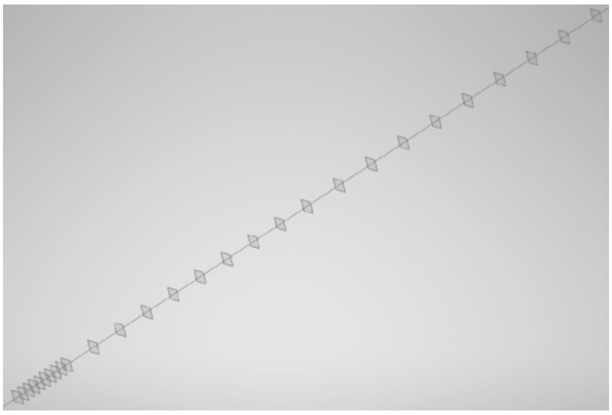


Figure 7: Graphical representation of the leg AC with its subsections

The fastest way to perform thirty optimizations in a row is to write a script that would call the *"main.m"* script which starts the optimization process for different locations on the scissor legs. The created *"start.m"* script is erasing content of the files that contain the location and energy of the prey, then it resets the counter and enters the **for** loop until the total number of optimizations has been completed. The counter provides the needed progression of the z parameter (position of the section for which the optimization is being performed) through optimizations, and it saves the value of the counter in the separate file.

The value of the counter then enters the *"main.m"* script that runs either the *"AC.m"* or *"BD.m"* script, depending on which leg is being optimized. Those two scripts contain geometrical characteristics of the scissors lift (such as the position of the hydraulic cylinder, total length of the legs, etc.), the formulas derived in the third chapter of this paper, and they are being executed before the *"Get_Function_details.m"* script because the values of the axial and shear force, and bending moment are needed for calculating the levels of stress. The reason why these scripts need to be run separately rather than within *"Get_Function_details.m"* script is because it shortens the time needed for performing each iteration within the optimization process. Considering that there could be thousand iterations in single optimization, and that there would be thirty optimizations like that one, the creation of additional script and placing the calculations of the forces and bending moment in it is justified as considerable amount of time is being saved.

The last change in the *"main.m"* file represents adding the two lines of code where each saves the values of the prey's location and energy at the end of each optimization, so when the whole process is finished, and all thirty optimizations are done, the optimal results for each subsection can be found in one text file.

After applying the purposed changes, the illustration shown in figure 3 takes the form represented in the figure 8.

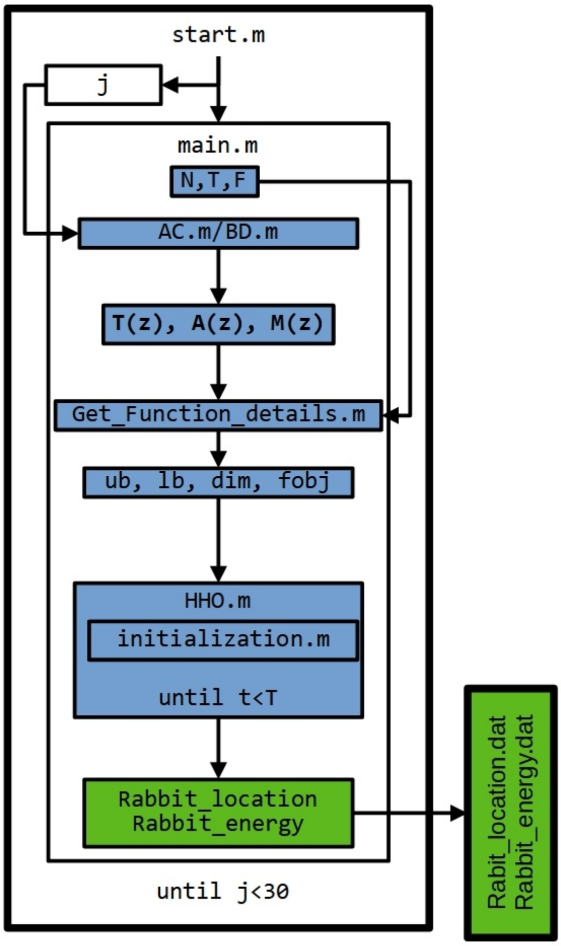


Figure 8: Illustration of the source code with modifications applied

5. RESULTS

For the platform that lifts the 1000 kg of load with centre of gravity located on $l_f = 0.5\ m$ distance from the pin D, in the lowest position of the platform, when the angle $\alpha = 7.5°$, and the parameters that define the position of the hydraulic cylinder: $a = 0.4 \cdot A$ m, $b = 0.3$ m, axial, shear, and bending moment diagrams for both AC and BD legs are shown in figures 9 and 10. Diagrams for the same platform when it is in the position where $\alpha = 75°$ are shown in figure 11 and figure 12.

By comparing the diagrams, it can be concluded that the load in the scissors lift legs is highest in the lowest position of the platform, making it the only relevant position of the platform for the optimization.

The thickness of the walls of the profile is set to $t = 6\,mm$. Boundaries of the searching area, according to the equation 37 are:

$$lb = [2 \cdot 0.6, 2 \cdot 0.6] = [1.2, 1.2] \quad (39)$$

$$ub = [100, 100] \quad (40)$$

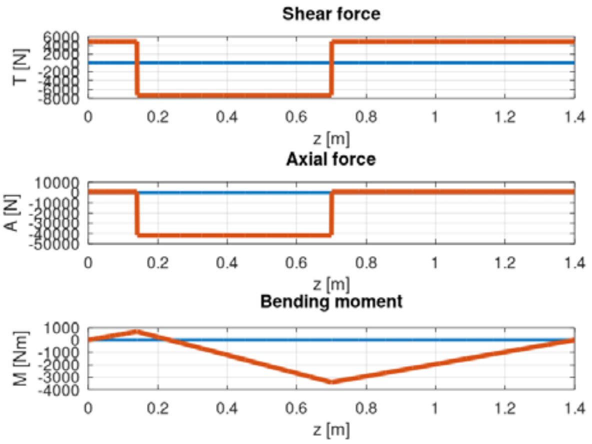


Figure 9: Static diagrams for the AC platform leg in the $a = 7.5°$ position

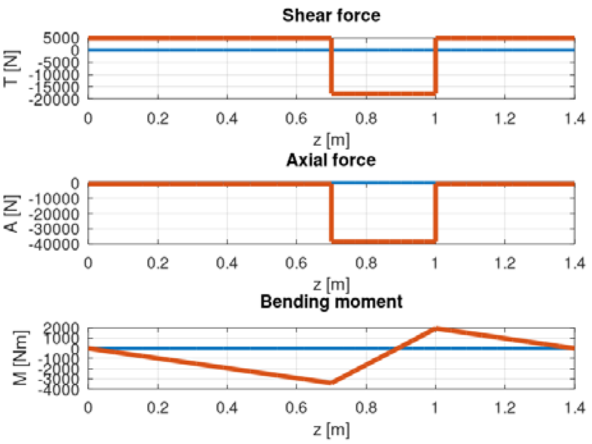


Figure 10: Static diagrams for the BD platform leg in the $a = 7.5°$ position

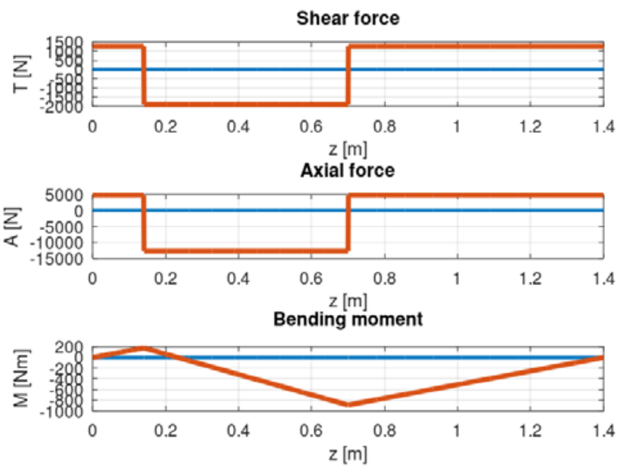


Figure 11: Static diagrams for the AC platform leg in the $a = 75°$ position

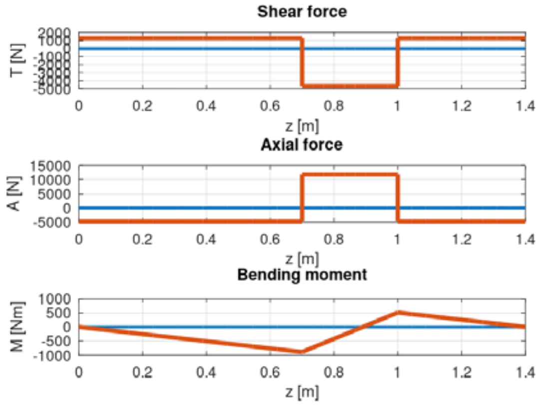


Figure 12: Static diagrams for the BD platform leg in the $a = 75°$ position

If the material of the scissors legs are being made from is structural steel S235, and safety factor is $\nu = 1.50$, allowed limits for both normal and tangential stress are:

$$\sigma_{dop} = 16\frac{kN}{cm^2}$$

$$\tau_{dop} = 9\frac{kN}{cm^2}$$

The number of hawks (size of initial population) was set to $N = 60$, and the maximum number of iterations was set to $T = 500$. These parameters represent the needed input information for the optimizer. After the optimization process is being completed, optimal values of the scissors legs, height and width are being shown in the table 1 and table 2.

Table 1. Results of the optimization process for the leg AC

$z\,[m]$	$h\,[cm]$	$g[cm]$	$\sigma_u\left[\frac{kN}{cm^2}\right]$
0	1.68	1.20	16
0.0156	1.99	1.59	16
0.0311	1.79	4.88	16
0.0467	2.03	4.25	16
0.0622	2.21	4.39	16
0.0778	2.41	4.40	16
0.0933	3.43	2.37	16
0.1089	2.84	4.25	16
0.1244	4.63	1.59	16
0.14	3.54	5.25	16
0.2022	4.10	2.56	16
0.2644	2.32	3.40	16
0.3267	1.64	4.06	16
0.3889	2.02	5.84	16
0.4511	2.48	5.96	16
0.5133	3.45	4.24	16
0.5756	3.28	6.48	16
0.6378	3.19	8.77	16
0.7	4.88	5.98	16
0.7778	6.88	2.45	16
0.8556	3.73	7.12	16
0.9333	3.61	6.38	16
1	2.88	7.75	16
1.0889	4.94	2.10	16
1.1667	2.99	4.24	16
1.2444	3.85	1.54	16
1.3222	2.63	1.65	16
1.4	2.39	1.20	6.32

Table 2. Results of the optimization process for the leg BD

$z\ [m]$	$h\ [cm]$	$g[cm]$	$\sigma_u\ \left[\frac{kN}{cm^2}\right]$
0	2.40	1.20	6.32
0.0778	2.27	2.25	16
0.1556	3.17	2.39	16
0.2333	2.81	4.69	16
0.3111	3.78	3.72	16
0.3889	3.06	6.93	16
0.4667	5.36	2.99	16
0.5444	4.27	5.62	16
0.6222	3.70	8.28	16
0.7	6.96	2.60	16
0.7333	4.31	7.90	16
0.7667	4.58	4.14	16
0.8	3.72	8.96	16
0.8333	3.85	4.40	16
0.8667	4.41	3.85	16
0.9	5.10	4.26	16
0.9333	6.97	2.71	16
0.9667	5.34	7.48	16
1	4.49	7.29	16
1.0444	3.79	8.60	16
1.0889	5.02	4.45	16
1.1333	5.36	3.21	16
1.1778	3.00	8.09	16
1.2222	3.10	6.00	16
1.2667	3.21	4.15	16
1.3111	3.28	5.87	16
1.3556	2.11	3.70	16
1.4	1.68	1.20	16

The values from table 1 and 2, as well as the ratio between the height and width of the profile across the length of the legs are being visualised in the figure 13 and figure 14.

The three-dimensional models of the scissors lift legs AC and BD made using the parameters from tables 1 and 2 are being shown in figures 15 and 16.

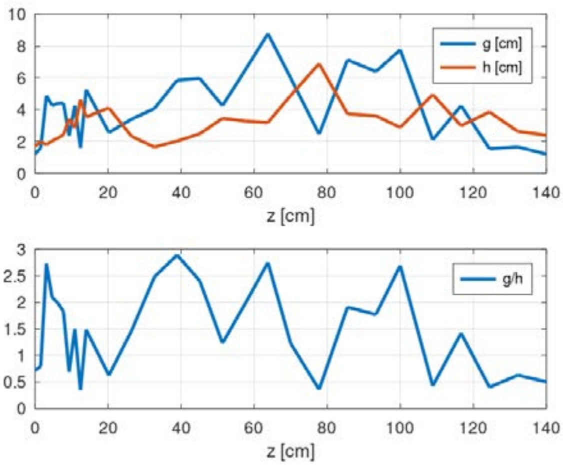


Figure 13. Visual representation of the values from the table 1

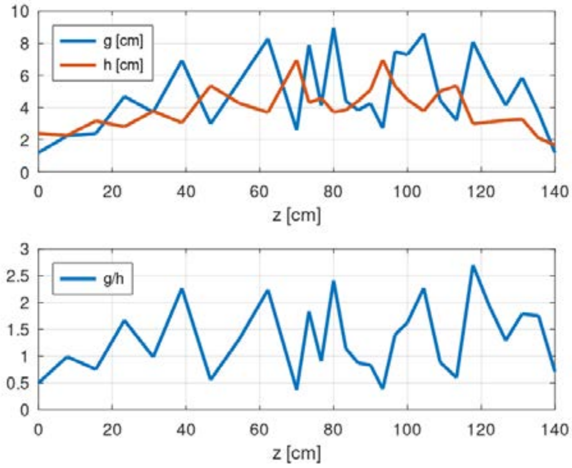
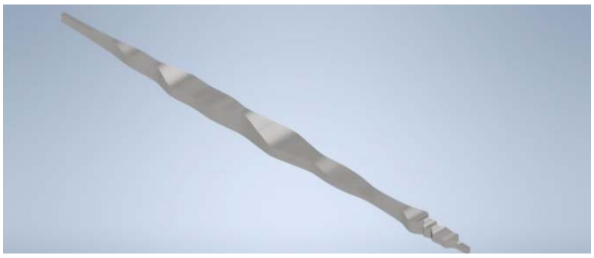


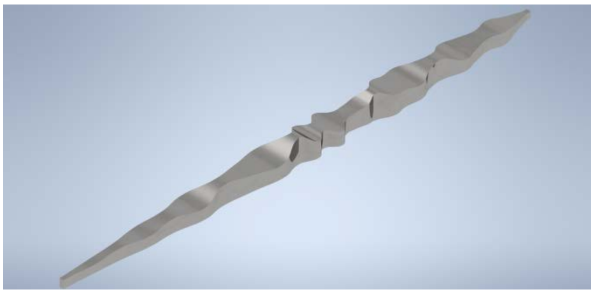
Figure 14. Visual representation of the values from the table 2



a)

b)

Figure 15: Three-dimensional model of the scissors lift leg AC: a) isometric view, b) cross section view



a)

b)

Figure 16: Three-dimensional model of the scissors lift leg BD: a) isometric view, b) cross section view

6. CONCLUSION

Comparing the results of the optimization represented on graphs displayed in figure 13 and figure 14 with the static diagrams displayed in figure 9 and figure 10, it can be concluded that the width of the profile $g(z)$ tends to be larger than the height $h(z)$ as the z gets further from the pins in both AC and BD leg.

Due to the constraint g_7 in the places where the pins pass through the legs, the height of the profile increases, while the width is getting shorter.

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