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OPTIMIZATION OF SCISSOR MECHANISM LIFTING PLATFORM MEMBERS USING HHO METHOD

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Abstract

Lifting platforms that employ the scissors mechanism have a variety of different constructions. In this paper, one of the solutions will be analysed, and the created model will be used for performing optimization using the novel Harris hawks optimization method, with the goal of reducing the mass of the members of the scissor mechanism.

Key words: *Harris hawks optimization, hydraulic scissors lift.*

1 INTRODUCTION

In the era of modern technologies where efficiency becomes imperative, the key is to reach the balance between the amount of used resources, safety and stability of built devices. Finding that balance has always been a challenge. Pursuing that goal many optimization techniques have been developed and used over time.

Lifting platforms are mechanical devices for vertical transport that are used for gaining easier access to high, unapproachable areas, and can be found in workshops where they are used by mechanics for car service and inspection, in airports [1], they are also used by the public services for working on electrical or telecommunication grids, firefighters and rescue services for evacuating people from high areas, etc.

Wide use of the lifting platforms induced variety of different construction solutions. The most of the same elements are usually present in all variants, such as platform on which the load is being placed, some sort of lifting mechanism which connects the platform to the metal base that is being fixated to some sort of metal or concrete foundation. The platform on top is usually consisted of flat metal sheet with protective fence. Rails or some other special equipment can be mounted on top of the metal sheet as well [2]. Lifting mechanism is the thing that differs the lifting platforms among which one of the most commonly used is the scissors mechanism.

Scissor mechanism is mechanism that consists of one or more scissors. Scissors are two beams connected in the middle with a pin. When actuator moves one beam, the movement is being transferred across the rest of the scissors that make up the lifting mechanism. One lifting platform that employes the scissor mechanism with multiple scissors stacked on top of each other is being displayed in figure 1.

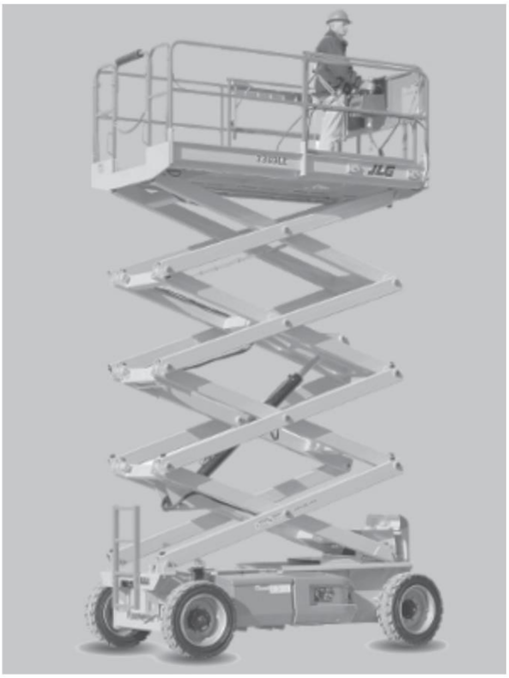

Fig. 1 *Lifting platform with multiple scissors* [2]

Multiple scissors are being used when higher altitudes need to be reached while only one is being used for lifting heavier loads.

Since the lifting platforms that use scissors mechanism are so commonly used, it is no surprise that a lot of different autors approached the problem of finding the optimal solution for the construction of the devices. In the paper [3] authors used parameter design to analyse one type of the scissor lifts, while authors in the paper [4] gave general analyses of scissor mechanism that does not depend of the actuator position nor the number of scissors in the mechanism. In the paper [5] the algorithm for designing a hydraulic scissor lifting platforms has been proposed, while in the paper [6] optimization of the members of the scissor pair had been conducted, but the dead load was not included in the proposed model.

In this paper, new mathematical model for one of the construction solutions will be proposed, and then used for structural optimization of the elements that make scissors mechanism by using Harris hawks optimisation method.

2 HARRIS HAWKS OPTIMIZATION METHOD

Harris hawks optimization method is P-metaheuristic optimization method, described in detail in the paper [7], inspired with the way that these birds hunt. Harris hawks are rare birds of prey that do not hunt alone, but rather in groups. They gather into hunting parties, search for prey together and split the catch among the group members. Two stages can be spotted in their hunting methodology: the exploration stage that occurs when the birds search the hunting area for the prey, and the exploitation stage when the spotted prey gets tackled and hunted down. The hawks represent possible solutions for the optimization problem, escaping prey represents the most optimal solution, while the energy of escaping prey represents value of the object function for the values stored in the location of the prey. Locations of hawks evolve through iteration following this rule:

$$X(t+1) = \begin{cases} X_{rand}(t) - r_1 |X_{rand}(t) - 2r_2 X(t)| & q \geq 0.5 \\ (X_{rabbit}(t) - X_m(t)) - r_3(LB + r_4(UB - LB)) & q < 0.5 \end{cases} \quad (1)\ [7]$$

…where $X(t+1)$ is location of hawks in $t+1$ iteration, t is the number of current iteration, $X_{rand}(t)$ is randomly chosen hawk from the population $X(t)$, $X_m(t)$ is average position of all hawks in the current iteration, LB and UB are limits of searching area, while the r_1, r_2 and r_3 are randomly generated numbers. Since this expression moddels the two ways that these birds search for prey, the q represents the probability that the hawks will choose one of the two strategies, which is also randomly generated.
Energy of the prey, which is modeled in the following way:

$$E = 2E_0\left(1 - \frac{t}{T}\right) \quad (2)\ [7]$$

…is also used for switching between exploration and exploitation phase within the algorhitm. The variables in the expression [2] are: E – energy of the prey, E_0 – randomly generated number in the interval (-1,1), T – total number of iterations.
All phases of the optimization process and how energy of the prey affects switching from one phase to another is being illustrated in the figure 2.

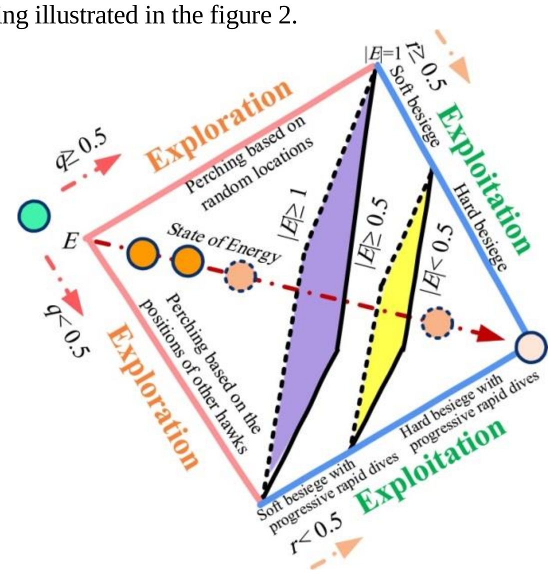

Fig. 2 *Different phases of Harris hawks optimization algorithm* [8]

The source code [9] written in Mathworks Matlab programming language is provided by original authors of the paper [7]. Simplified illustration of the original source code structure is being shown in figure 3. It is consisted of one main.m script in which the size of initial population *N* is being defined, as well as the total number of iterations *T*, and the name of the object function. Those values represent input for the Get_Function_details.m function which outputs the value of the object function *fobj*, dimension of the optimization problem *dim*, as well as limits of searching area *ub* and *lb*. The HHO.m function is where the Harris hawks algorithm is being implemented. It first generates the initial population of hawks and, by using values of object function that is being calculated using Get_Function_details function, evolves the position of hawks towars the optimal solution going through all the previously described stages.
The Get_Function_details function is the one that has to be adapted to every specific optimization problem.

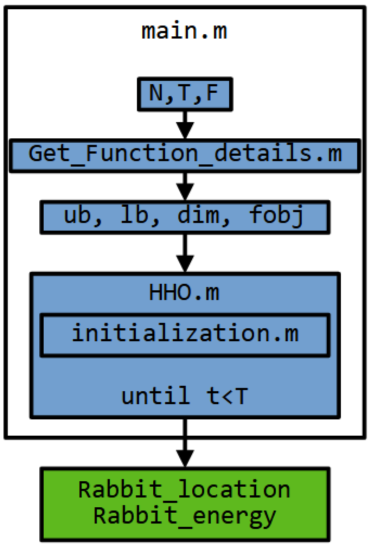

Fig. 3 *Illustration of the source code of the HHO algorithm* [10]

3 BUILDING THE MODEL

The construction solution of the lifting platform that uses scissor mechanism as lifting mechanisam that is analyzed is ilustrated in figure 4.

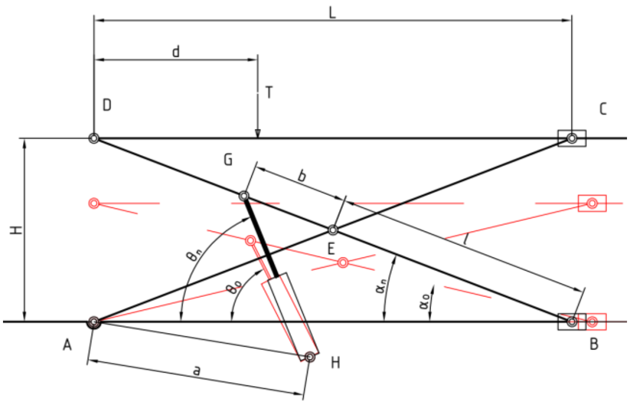

Fig 4. *Illustration of lifting platfom with scissor mechanism*

The observed structure displayed in figure 4 consists of upper platform on top of which the load is being added. The platform is connected to the scissor mechanism over pin D and slider C. The distance between the pin D and slider C is not constant since it changes with the altitude of the platform, and it is marked with the letter L. Two equally long beams, AC and BD, connected in the middle with a pin E make up the scissor mechanism. The actuator GH is connected to the beam BD over pin G on distance b from the pin E. The pin A makes the fixed support with the ground, while the beam BD is connected to the ground over the slider B. The load and the weight of the platform are replaced with one active force T which is placed on distance d from the pin D. Free body diagram of described structure is represented in figure 5.

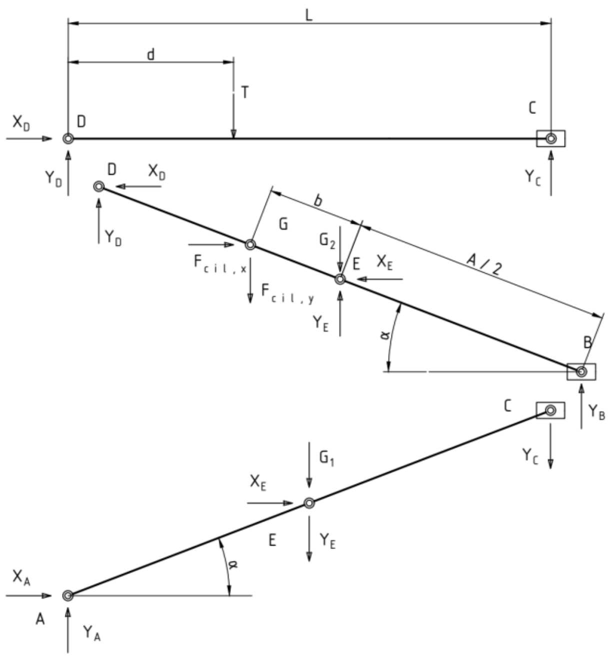

Fig. 5 *Free body diagram of the lifting platform*

Since the lifting speeds of the platforms are not high, inertia forces can be neglected, and this whole construction can be observed as static. Hence, the static equations can be derived for the system represented in figure 5.
Static equations for the platform CD:

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

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

$$\Sigma M_{i(E)} = 0: Y_C L - T \cdot d = 0 \tag{5}$$

Static equations for the beam BD:

$$\Sigma X_i = 0: -X_D + F_{cil,x} - X_E = 0 \tag{6}$$

$$\Sigma Y_i = 0: -Y_D - F_{cil,y} + Y_E + Y_B - G_2 = 0 \tag{7}$$

$$\begin{aligned}\Sigma M_{i(E)} = 0: &\frac{L}{2} \cdot Y_B + \frac{H}{2} \cdot X_D + \frac{L}{2} \cdot Y_D \\ &- F_{cil,x} b \sin(\alpha) \\ &+ F_{cil,y} b \cos(\alpha) = 0\end{aligned} \tag{8}$$

Static equations for the platform AC:

$$\Sigma X_i = 0: X_A + X_E = 0 \tag{9}$$

$$\Sigma Y_i = 0: \mathrm{Y_A} - \mathrm{Y_E} - Y_C - G_1 = 0 \tag{10}$$

$$\Sigma M_{i(E)} = 0: -\frac{L}{2} \cdot Y_A + \frac{H}{2} \cdot X_A - \frac{L}{2} Y_C = 0 \tag{11}$$

In the equations (6), (7), and (8), reactions from the cylinder had been replaced with equvalent projections on the axes of global coordinate system:

$$F_{cil,x} = F_{cil} \cos(\theta)\,; F_{cil,y} = F_{cil} \sin(\theta) \tag{12}$$

The angle θ can be calculated with the following expression:

$$\theta = \arctan\frac{(l+b)\sin(\alpha) + a\sin(\beta)}{a\cos(\beta) - (l-b)\cos(\alpha)}, \quad \theta \in \left[0, \frac{\pi}{2}\right) \cup \left(\frac{\pi}{2}, \pi\right) \tag{13 [6]}$$

The forces represented with letters G_1 and G_2 represent the weight of the beams.
These equations can be written in matrix form which is suitable for solving with the use of computer:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & L & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & \cos(\theta) & -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & -\sin(\theta) & 0 & 0 & 1 & 1 \\ \frac{H}{2} & \frac{L}{2} & 0 & 0 & b\cos(\theta-\alpha) & 0 & 0 & 0 & \frac{L}{2} \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & -\frac{L}{2} & \frac{H}{2} & 0 & 0 & -\frac{L}{2} & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} X_D \\ Y_D \\ Y_C \\ X_A \\ F_{cil} \\ X_E \\ Y_A \\ Y_E \\ Y_b \end{bmatrix} = \begin{bmatrix} 0 \\ T \\ T \cdot d \\ 0 \\ G_2 \\ 0 \\ 0 \\ G_1 \\ 0 \end{bmatrix} \tag{14}$$

When the system of equations (14) gets solved, the reactions in joints and live load can be projected to beams local axes, and the axial, shear and momentum diagrams can be created. Based on those diagrams, the most critical spot can be discovered.
The equations needed for creating the diagrams for the beam BD, shown in figure 6, are:

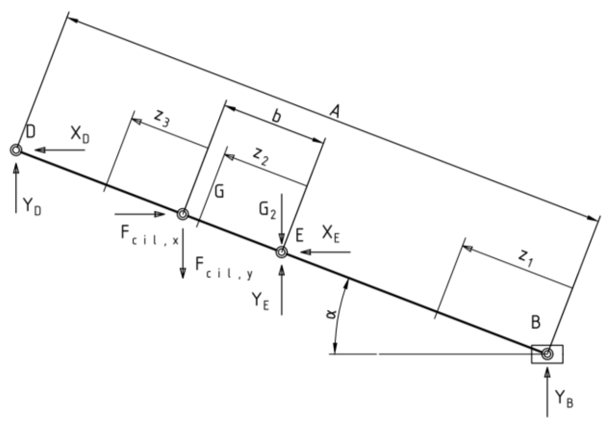

Fig. 6 *Beam BD*

$$0 \le z_1 < \frac{A}{2}$$

$$\mathrm{A}(\mathrm{z_1}) = -Y_B \sin(\alpha) \tag{15}$$

$$\mathrm{T}(\mathrm{z}_1) = Y_B \cos(\alpha) \tag{16}$$

$$M_i(z_1) = Y_B \cos(\alpha)\, z_1 \tag{17}$$

$$0 \le z_2 < b$$

$$\mathrm{A}(\mathrm{z}_2) = -Y_B \sin(\alpha) - X_E \cos(\alpha) - Y_E \sin(\alpha) + G_2 \sin(\alpha) \tag{18}$$

$$\mathrm{T}(\mathrm{z}_2) = Y_B \cos(\alpha) - G_2 \cos(\alpha) + Y_E \cos(\alpha) - X_E \sin(\alpha) \tag{19}$$

$$M_i(z_2) = Y_B \cos(\alpha)\left(\frac{A}{2} + z_2\right) - G_2 \cos(\alpha)\, z_2 + Y_E \cos(\alpha)\, z_2 - X_E \sin(\alpha)\, z_2 \tag{20}$$

$$0 \le z_3 < \frac{A}{2} - b$$

$$\mathrm{A}(\mathrm{z}_3) = -Y_B \sin(\alpha) - X_E \cos(\alpha) - Y_E \sin(\alpha) + G_2 \sin(\alpha) + F_{cil,y} \sin(\alpha) + F_{cil,x} \cos(\alpha) \tag{21}$$

$$\mathrm{T}(\mathrm{z}_3) = Y_B \cos(\alpha) - G_2 \cos(\alpha) + Y_E \cos(\alpha) - X_E \sin(\alpha) - F_{cil,y} \cos(\alpha) + F_{cil,x} \sin(\alpha) \tag{22}$$

$$M_i(z_3) = Y_B \cos(\alpha)\left(\frac{A}{2} + b + z_3\right) - G_2 \cos(\alpha)\,(b + z_3) + Y_E \cos(\alpha)\,(b + z_3) - X_E \sin(\alpha)\,(b + z_3) + F_{cil,x} \sin(\alpha)\, z_3 - F_{cil,y} \cos(\alpha)\, z_3 \tag{23}$$

The equations needed for creating the diagrams for the beam AC, shown in figure 7, are:

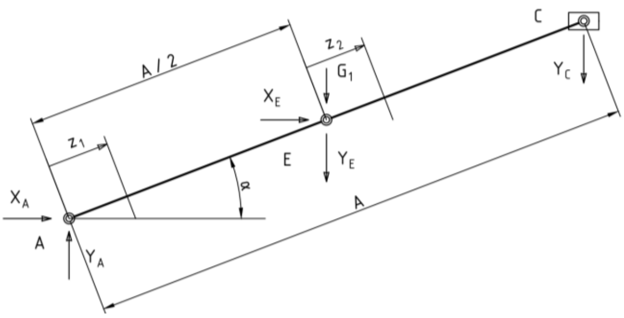

Fig. 7 *Beam AC*

$$0 \le z_1 < \frac{A}{2}$$

$$\mathrm{A}(\mathrm{z}_1) = Y_A \sin(\alpha) + X_A \cos(\alpha) \tag{24}$$

$$\mathrm{T}(\mathrm{z}_1) = Y_A \cos(\alpha) - X_A \sin(\alpha) \tag{25}$$

$$M_i(z_1) = -Y_A \cos(\alpha)\, z_1 + X_A \sin(\alpha)\, z_1 \tag{26}$$

$$0 \le z_2 < \frac{A}{2}$$

$$\mathrm{A}(\mathrm{z}_2) = Y_A \sin(\alpha) + X_A \cos(\alpha) + X_E \cos(\alpha) - G_1 \sin(\alpha) - Y_E \sin(\alpha) \tag{27}$$

$$\mathrm{T}(\mathrm{z}_2) = Y_A \cos(\alpha) - X_A \sin(\alpha) - Y_E \cos(\alpha) - X_E \sin(\alpha) - G_1 \cos(\alpha) \tag{28}$$

$$M_i(z_2) = -Y_A \cos(\alpha)\left(\frac{A}{2} + z_2\right) + X_A \sin(\alpha)\left(\frac{A}{2} + z_2\right) + X_E \sin(\alpha)\, z_2 + G_1 \cos(\alpha)\, z_2 + Y_E \cos(\alpha)\, z_2 \tag{29}$$

There are two characteristic positions of the platform for which the reactions should be calculated:

- when the platform reaches its top position;
- when the platform reaches its lowest position.

The relevan position is the position in which the reactions take higher values.

4 OBJECTIVE FUNCTIONS, LIMITS OF SEARCHING AREA, AND CONSTRAINTS

4.1. Objective function

The goal of the optimization is to find geometrical characteristics of the memebers of scissor mechanism for which the masses of the beams are minimal, but the stresses in them do not exceed the allowed values. Masses of the beams can be calculated following these expressions:

$$m_1 = S_1 \cdot A \cdot \rho \qquad m_2 = S_2 \cdot A \cdot \rho \tag{30}$$

...which combined make the object function for the optimization process:

$$\mathrm{o} = m_1 + m_2 \tag{31}$$

..where m_1 and m_2 are masses of beams AC and BD respectively, S_1 and S_2 are surfaces of the cross sections of the beams, and ρ is the density of material from which the beams were made.

4.2. Limits of the searching area

If the cross section of the beams is in the shape of box, shown in figure 8, the variables that can be optimized are height h, width b and thickness of the wall t. The limis of the searching area can be deffined as follows:

$$LB = [b_{1,min}, h_{1,min}, t_{1,min}, b_{2,min}, h_{2,min}, t_{2,min}] \tag{32}$$

$$UB = [b_{1,max}, h_{1,max}, t_{1,max}, b_{2,max}, h_{2,max}, t_{2,max}] \tag{33}$$

...where LB is vector which contains the lower boundaries for the variables that are being optimized, and UB is a vector which contains their upper boundaries. By observing the shape of the crossection displayed in the figure 8 it can be concluded that the minimal values for the width and height of the given crossection are double value of the wall thickness, so the expression (32) takes up the following form:

$$LB = [2 \cdot t_{1,max}, 2 \cdot t_{1,max}, t_{1,min}, 2 \cdot t_{2,max}, 2 \cdot t_{2,max}, t_{2,min}] \tag{34}$$

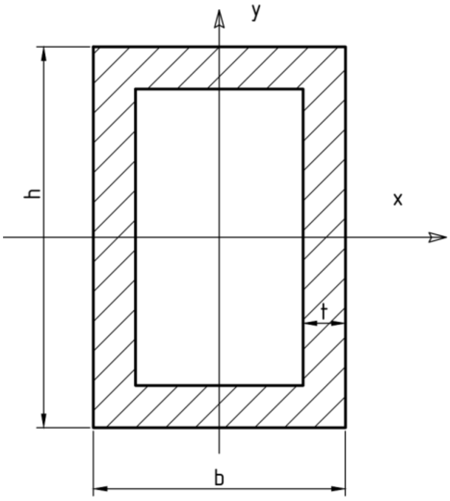

Fig. 8 *Cross section of the beams*

4.3. Constraints

Constraints play important role in the optimization process and that role is to keep the values of variables, for which the object function is being calculated, within the appropriate range. When it comes to optimization of the beams that are members of scissor mechanism, two sets of constraints can be applied: geometrical constraints and stress constraints, where the former keep variables in defined range so neither of dimensions can take extremly high or low values compared to the other relevant variables, and the latter are in place to ensure that norma, shear and equivalent stresses do not exceed allowed values for the given material.

The geometrical characteristics of the cross section can be calculated using the following expressions:

$$S = b \cdot h - (b - 2 \cdot t)(h - 2 \cdot t) \tag{35}$$

$$S_x = \frac{(g - 2 \cdot t) \cdot t \cdot (h - t)}{2} + \frac{h^2 \cdot t}{4} \tag{36}$$

$$I_x = 2 \cdot \left(\frac{(b - 2 \cdot t) \cdot t^3}{12} + (b - 2 \cdot t) \cdot t \cdot \left(\frac{h - t}{2} \right)^2 \right) + \frac{t \cdot h^3}{6} \tag{37}$$

...where S is the surface area of the cross section, S_x is the first momentum of area, and I_x is the moment of inertia.

Normal stress σ_N, as a combination of the stress from the axial forces σ_A and bending momentums σ_M, shear stress τ and equivalent stress σ_e can be calculated by using the following expressions:

$$\sigma_N = \sigma_A + \sigma_M = \frac{A}{S} + \frac{M_x}{I_x} \cdot y_{max} \tag{38}$$

$$\tau = \frac{T \cdot S_x}{I_x \cdot t} \tag{39}$$

$$\sigma_e = \sqrt{\sigma_N^2 + 3 \cdot \tau^2} \tag{40}$$

Based on the previous equations, the stress constrants can be deffined as:

$$g(1) = \sigma_{e,max,1} - \sigma_{dop} < 0 \tag{41}$$

$$g(2) = \sigma_{e,max,2} - \sigma_{dop} < 0 \tag{42}$$

$$g(3) = |\sigma_{N,1}| - \sigma_{dop} < 0 \tag{43}$$

$$g(4) = |\sigma_{N,2}| - \sigma_{dop} < 0 \tag{44}$$

$$g(5) = |\tau_1| - \sigma_{dop} < 0 \tag{45}$$

$$g(6) = |\tau_2| - \sigma_{dop} < 0 \tag{46}$$

...where the σ_{dop} is the allowed stress intensity for the used material.

Geometrical constraints can be deffined as:

$$g(7) = \frac{b_1}{h_1} < 3 \tag{47}$$

$$g(8) = \frac{b_2}{h_2} < 3 \tag{48}$$

$$g(9) = \frac{h_1}{b_1} < 3 \tag{49}$$

$$g(10) = \frac{h_2}{b_2} < 3 \tag{50}$$

$$g(11) = \frac{h_1}{t_1} > 2 \tag{51}$$

$$g(12) = \frac{h_2}{t_2} > 2 \tag{52}$$

4.4. Adjustments of the source code

In equations (38) and (39) it can be seen that the values of stress depend on the values of the loads, and the loads are being changed as the weight of the beams change through iterations.

Inside of the Get_Function_details function of the source code the equations derived in previous chapter, object function, limits of searching area, and constraints, should be applied. New function model.m can be created to improve readability of the code, and that function should contain the equations derived in the chapter 3, so the structure of the code can be illustrated as shown in figure 9.

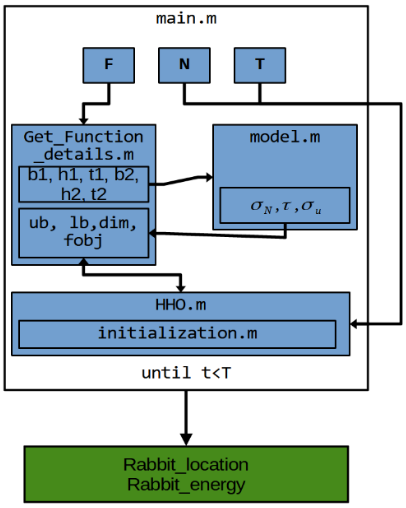

Fig. 9 *Illustration of adjusted HHO source code*

The newly created function takes the optimized values b_1, h_1, t_1, b_2, h_2 and t_2, calculates the loads and searches for critical spot where the equivalent stress is maximum, for both critical positions. When the critical spot is found, values of normal, shear and equivalent stresses is being stored and returned to the Get_Function_details function where the value of object function gets calculated with applied constraints.

5 RESULTS

For the platform that lifts the 1t of load with centre of gravity located on $d = 0{,}42\ m$ distance from the pin D, and if the platform reaches its lowest position when the $\alpha = 20°$, and the highest position when the angle $\alpha = 60°$, and the parameters that define the position of the actuator are: $a = 0{,}56\ m, b = 0{,}28\ m, \beta = 10°$, the length of both AC and BD beams made of steal S235 are $A = 1{,}4\ m$, when the boundaries of the searching area deffined as:

$$LB = [2.4, 2.4, 0.4, 2.4, 2.4, 0.4] \quad (53)$$

$$UB = [100, 100, 1.2, 100, 100, 1.2] \quad (54)$$

…for the optimization parameters:

- $N = 60$ – the size of population
- $T = 1500$ – the total number of iterations

…the results of the optimization are shown in the table 1.

Table 1 Results of the optimization

	AC	BD	Limits
b [mm]	48,109	45,094	1000
h [mm]	24	79,615	1000
t [mm]	4	4	12
m [kg]	5,6365	10,2611	-
h/b [-]	0,4989	1,7655	<3
b/h [-]	2,0045	0,5664	<3
h/t [-]	6	19,9037	>3
b/t [-]	12,0273	11,273	>3

6 CONCLUSION

When the results displayed in table 1 are analysed, the following conclusions can be derived:

If the cross section of the beam that connects to the actuator is in the shape of a box as displayed in figure 8, the height of the cross section should be bigger than the width;

The width of the cross section of the beam that is not connected to the actuator should have a higher value than the height;

The walls of the cross section of both beams should be as thin as possible.

Further research is needed to include the local stability in the mathematical model because the thin walls of the cross section can have an impact on the local stability of the beams.

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