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MULTIPLE OPTIMISATION ALGORITHM COMPARISON ON THE HEAVY-WEIGHT LOADING RAMP MECHANISM OPTIMISATION PROBLEM

Predrag MLADENOVIĆ[1]
Marko TODOROVIĆ[1]
Goran MARKOVIĆ[1]
Nebojša B. ZDRAVKOVIĆ[1]
Mile SAVKOVIĆ[1]
Goran PAVLOVIĆ[2]

[1)]*Faculty of mechanical and civil engineering in Kraljevo, University of Kragujevac, Kraljevo (Serbia)*
[2)] *University of Niš, Faculty of Electronic Engineering, Niš, (Serbia)*

Abstract

Several metaheuristic optimisation algorithms were used and compared to obtain an optimal solution for the geometric parameters of a mechanism used for a heavy-weight loading ramp. The optimisation goal was to reduce the force in the hydraulic cylinder to start the ramp, i.e. to lower and raise it. For the optimisation process, a mathematical model that describes the movement of the mechanism members was established, and the dimensions of the corresponding members of the mechanism were determined, as well as the positions of the characteristic points of the mechanism, which enables the most negligible force in the hydraulic cylinder used to start the ramp. A comparative analysis of the results obtained by different algorithms was done.

***Keywords**: Optimisation algorithms, loading ramp, comparative analysis, mechanism design, metaheuristic approach*

1 INTRODUCTION

Several solutions can be found for a specific problem or purpose that will fulfil specific requirements to a greater or lesser extent. Apart from whether a solution will meet particular needs, other criteria can be considered when choosing it.

Nowadays, the overall price of the solution plays a big, and very often decisive, role in this choice. In mechanical engineering, as well as in other areas of engineering, the price of a machine or device mainly depends on the amount of material used for its production and the price of the components installed in it. By reducing these amounts of material and installing smaller components, the price of the entire device, i.e. construction, will be proportionally reduced.

This paper discusses the mechanism for raising and lowering the ramp used to load heavy vehicles onto a trailer for their transport. This device is prevalent because the need to transport machines for various purposes has increased. After all, the number of infrastructure projects has also increased. There is a large number of already implemented solutions that have been used so far but are still used in some cases. Some of these solutions are described in papers [1-3]. Depending on the degree of automation, there are simpler and more primitive solutions, as shown in Fig. 1, where the loading ramp is being moved manually, using human power, or possibly using the working device of the machine being transported.

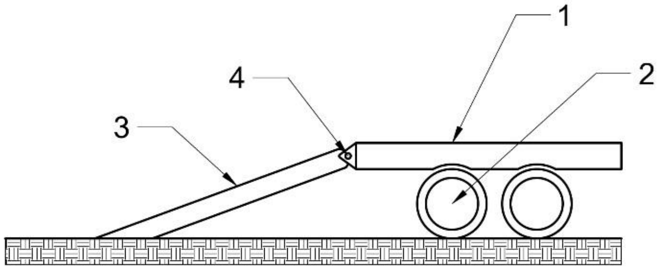

***Fig. 1** Illustration of the solution with manual manipulation of the loading ramp*

Fig. 1 shows components such as (1) the carrying platform, (2) pneumatics, (3) loading ramp, and (4) loading ramp support.

Over time, springs were added to the original first solution to help raise the loading ramp, as shown in Fig. 2. where can be seen components such as (1) the carrying platform, (2) pneumatics, (3) the loading ramp, and (4) swathe springs.

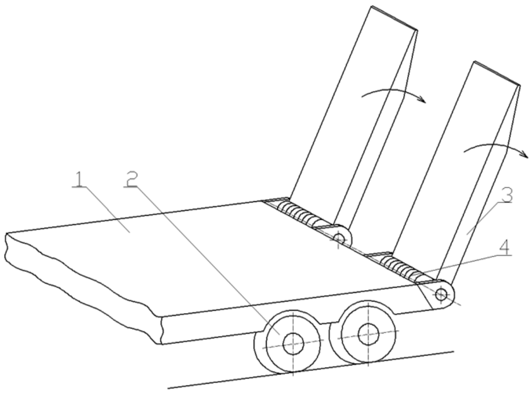

***Fig. 2** Solution with swathe springs [2]*

The solution, which eliminated the use of human power or additional devices, involved the installation of a hydraulic cylinder near the ramp support on the trailer.

Although this solution eliminated human participation in moving the ramp, it still has disadvantages regarding the load on the members of the mechanism and the force required to start the ramp.

By choosing more carefully the place of support of the hydraulic cylinder and its connection with the ramp, the manipulation of the ramp can be achieved with a smaller amount of energy consumed and less load on the members of the ramp mechanism. The mechanism scheme that enables this is shown in Fig. 3 and is described in more detail in the paper [3].

The components of the system shown in Fig. 3 are: (1) the carrying platform, (2) pneumatics, (3) loading ramp, (4) loading ramp support, (5) the vehicle being transported, (6) hydro-cylinder support, (7) a lever of a complex shape, (8) hydro-cylinder, (9) mechanism rod.

The advantage of using this solution is that the lever system reduces the force in the hydraulic cylinder used to start the ramp.

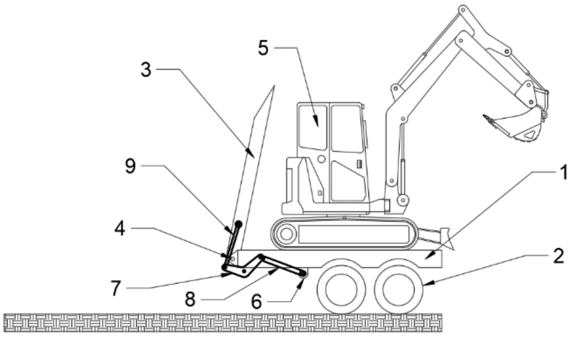

Fig. 3 *Illustration of the solution with a system of levers and a hydro-cylinder [3]*

The force reduction is made possible using a lever system that increases the force arm that balances the entire mechanism. The larger the arm of the force, the greater the normal distance of the axis of the mechanism member from the point of support, and the smaller the force required for balancing the mechanism will be. Influence on the reduction of force in the hydraulic cylinder can be achieved by choosing the appropriate lengths of the mechanism members, i.e. the length of the levers, defining the angle of the compound lever, and choosing the appropriate support positions, both the lever support and the hydraulic cylinder support. Appropriate dimensions and positions can be found through the optimisation process, which can be found in the paper [4].

Optimisation begins with creating a mathematical model to describe the corresponding phenomenon or mechanism mathematically. Of course, it is necessary to introduce certain limits for optimisation variables and constraints. Metaheuristic algorithms were used in this paper, and given that several different algorithms were used, a comparative analysis of the obtained results was given. Some algorithms give good results for a specific category of mathematical problems and models, but some algorithms are not suitable for solving them. Indeed, both algorithms give some results, but only certain ones give favourable results. That is, their objective function has a superior value compared to other algorithms. At the beginning of the research, before the optimisation process, we did not know which algorithms would be suitable for application to the given problem, so it is necessary to try several different algorithms and single out those that achieve the best results.

2 MATHEMATICAL MODEL

Mathematical models can significantly facilitate the implementation of scientific research and obtaining specific scientific results. First of all, this refers to the fact that using the model can avoid conducting experiments on authentic objects, which can be extremely expensive and demanding. In addition to the high cost of experiments, a big challenge is spending precious time organising experiments on authentic objects, which often cannot even be performed due to various limitations.

In this case, the mathematical model consists of a series of equations that simulate the movement of the mechanism members. The movement of the characteristic points of the mechanism and the change in the angles that the axes of individual members of the mechanism overlap with the horizontal axis are described in more detail in the paper [3]. The mathematical model used for the analysis is shown in Fig. 4.

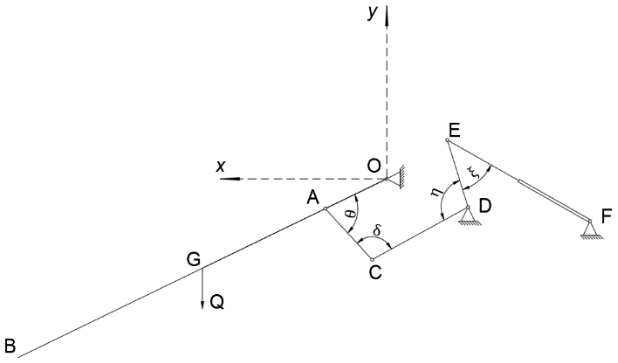

Fig. 4 *Mechanism wire model*

Based on Fig. 4, it can be concluded that the wire model of the mechanism was used for the mathematical model, which implies that the corresponding line elements correspond to the axes of the mechanism members. This way of displaying elements is possible because optimisation aims to obtain the most favourable lengths of the elements of the mechanism, not their cross-sections.

The shown wire model is located in the vertical plane, where the coordinate origin is defined at point O, representing the point of support of the loading ramp on the trailer.

The markings that can be seen in Fig. 4 are described in Table 1.

Table 1 Description of mechanism member labels

O	Coordinate system origin
A	The attachment point of the lever to the ramp
G	The centre point of the ramp
B	The endpoint of the ramp
C	The connection point between the levers of the mechanism
D	The point of support of the compound lever

	on the trailer chassis
E	The connection point between the lever of the mechanism and the hydraulic cylinder
F	The point of support of the hydraulic cylinder on the chassis of the trailer

The angles θ, δ, and ξ are the angles between the axes of the levers of the mechanism and can be seen in Fig 4.

Given that the vertices of these angles represent the pins that connect the mechanism's levers, the arms' mutual movement of these angles is not constrained so that the mentioned angles change their values during the movement of the mechanism. Points C, D, and E form a member of the mechanism called a compound lever. This component is obtained by joining the levers marked CD and DF, thus forming the angle between them which is marked with η. This constant angle represents one of the variables that are the subject of the optimisation process.

The lengths of the members of the mechanism used in the formation of the mathematical model are given in Table 2.

Table 2 Length labels for the optimisation process

OB	L_0	The length of the loading ramp
OA	L_1	The distance between the connection point of the lever and the ramp
AC	L_2	Mechanism lever length
CD	L_3	The length of the compound lever segment of the mechanism
DE	L_4	The length of the compound lever segment of the mechanism
FE	L_{FE}	The current length of the hydraulic cylinder
DF	L_{DF}	The distance between the supports of the compound lever and the hydraulic cylinder
OD	L_{OD}	The distance between the supports of the compound lever and the loading ramp

The mechanism for raising and lowering the loading ramp is loaded by the force originating from the self-weight of the members of the mechanism. In this case, only the mass of the loading ramp is known, so its effect was included in the consideration, while the effects of the masses of the members of the mechanism were neglected due to the lack of data on their cross-sections. The assumed mass of the loading ramp is 500 kg, and the weight force originating from this mass is marked with FQ, acts at point G and is directed vertically downward, as can be seen in Fig. 4. The initial and final positions of the loading ramp and members of the mechanism for its raising and lowering are shown in Fig. 5.

Based on these figures, it can be concluded that for creating a mathematical model, it was necessary to define auxiliary angles that enable the creation of a connection between the movements of certain mechanism members.

The procedure for determining the mechanism's appropriate lengths, angles and movement is described in detail in the paper [3], so only some main equations of the described model will be listed here.

The length that defines the stroke of the hydraulic cylinder, as one of its most essential characteristics, is calculated using Eq. (1).

$$L_{FE} = \sqrt{(X_E(i) - X_F)^2 + (Y_E(i) - Y_F)^2} \tag{1}$$

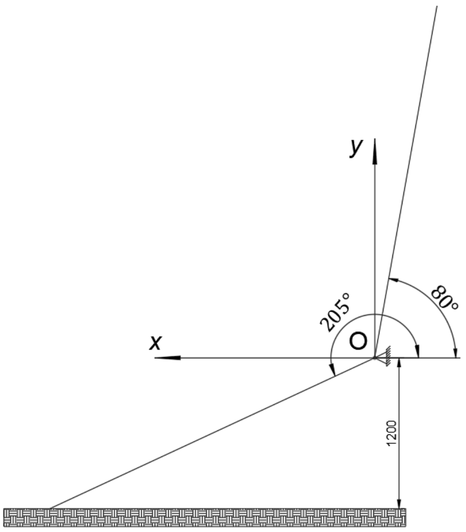

Fig. 5 *The position of the ramp at the beginning and end of the movement [3]*

Figures 6 and 7 allow the creation of equations describing the mechanism's movement in the vertical plane.

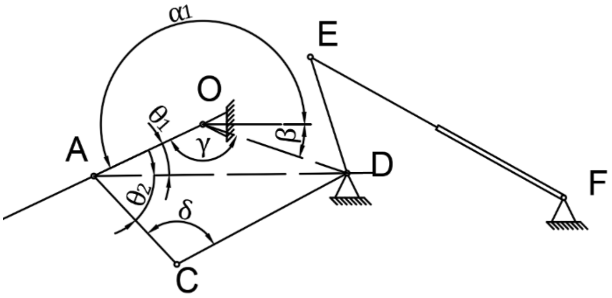

Fig. 6 *Auxiliary angles between members of the mechanism [3]*

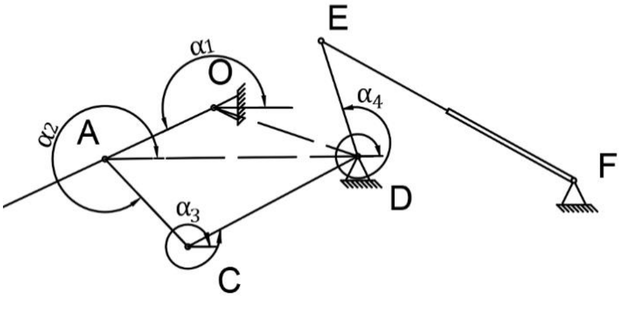

Fig. 7 *Angles between the mechanism members and the horizontal axis [3]*

Given that the ramp occupies a range of angles with the horizontal axis, a counter was introduced that defines the angle change when moving the ramp. That counter is denoted by *i* so that when *i* has the value 1, the ramp's angle with the horizontal axis is α_1=80 degrees.

The stroke of the hydraulic cylinder, which is required to achieve the desired movement of the ramp from the initial to the final position, is calculated using Eq. (2).

$$stroke = L_{FE}(end) - L_{FE}(start) \tag{2}$$

The stroke of the hydraulic cylinder is obtained as the difference in the length of the hydraulic cylinder at the end and the beginning of the movement.

The characteristic of the hydraulic cylinder based on which its selection is made is the force that needs to be realised to enable movement. The equations used to calculate the force that needs to be realised in the hydraulic cylinder derive from the equilibrium conditions of the mechanism. This equilibrium condition implies two-moment equations from which specific forces are obtained. The moment equations are obtained based on Fig. 8 and Fig. 9. The impact of the position of the hydraulic cylinder mounting point can be seen in [4].

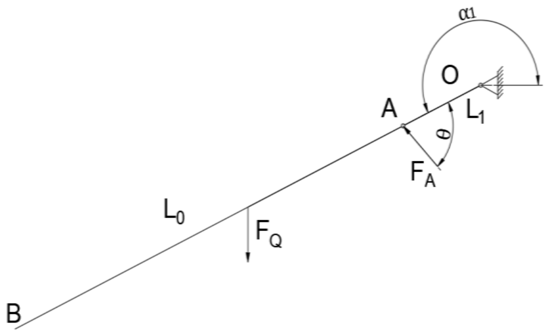

Fig. 8 *The wire model described by Eq. (3) [3]*

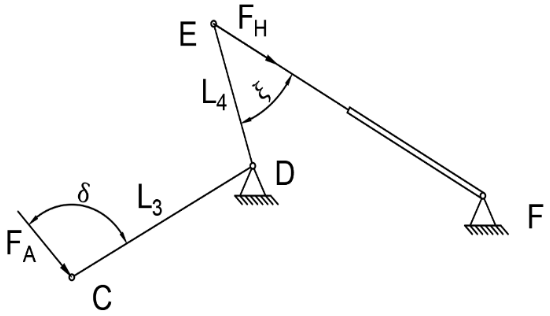

Fig. 9 *The wire model described by Eq. (4) [3]*

$$\sum M_O = Q \cdot \frac{L_0}{2} \cdot \cos(\alpha_1) - F_A \cdot L_1 \cdot \sin(\theta) \tag{3}$$

$$\sum M_D = F_A \cdot L_3 \cdot \sin(\delta) - F_H \cdot L_4 \cdot \sin(\xi) \tag{4}$$

To prevent the movement of the members of the mechanism, i.e. to achieve balance, it is necessary to equalise the equations (3) and (4) to zero. After that, the equations that enable the calculation of the force in the hydraulic cylinder are obtained and shown in Eq. (5) and Eq. (6).

$$F_A(i) = \frac{-F_Q \cdot L_0 \cdot \cos(\alpha_1(i))}{2 \cdot L_1 \cdot \sin(\theta(i))} \tag{5}$$

$$F_H(i) = \frac{-F_A(i) \cdot L_3 \cdot \sin(\delta(i))}{L_4 \cdot \sin(\xi(i))} \tag{6}$$

The final equation for calculating the force in the hydraulic cylinder is given by Eq. (6), and it can be concluded that depending on the position of the ramp, it changes its value.

3 DESCRIPTION OF THE OPTIMISATION ALGORITHMS

In recent years, there has been a proliferation of novel general-purpose metaheuristic algorithms. No free lunch theorem [5-6] justifies further development and research since, according to it, no single optimisation algorithm gives the best solution for all of the optimisation problems. Authors of the papers which present the algorithms, such as [7-9], usually provide some results for the most common benchmark examples so the newly presented algorithm can be compared to the existing ones. However, the functions used to compare the efficiency of the algorithms can be misleading when the algorithm has to be chosen for solving a specific engineering problem.

For this paper, the performance of four recent metaheuristic optimisation algorithms was compared on the same optimisation problem in the same conditions in the search for the optimal solution: Supply-Demand-Based Optimisation (SDO) [10], Marine predators algorithm (MPA) [11], Slime mould algorithm (SMA)[12], and Search and rescue optimisation algorithm (SAR) [13]. Like other metaheuristic algorithms, they all consist of exploration and exploitation phases interchanging through the optimisation processes. The exploration phases rely on picking random values from the given interval of optimised variables, while the exploration phases rely on the evolution of the solution through the iterations, also employing some randomness factor. The exploration phase aims to avoid the algorithm converging to a local optimum, while the exploitation phase represents the search around the local minima.

4 OBJECTIVE FUNCTIONS, LIMITS OF SEARCHING AREA, AND CONSTRAINTS

4.1. Objective function

The optimisation process involves defining the objective function by which the formed mathematical model is used to obtain a variable's minimum or maximum values. In this case, the force in the hydraulic cylinder required to move the mechanism is minimised. The equation for calculating the force in the hydraulic cylinder depending on the position of the ramp during its movement was obtained using a mathematical model. In general terms, the objective function is defined by Eq. (7).

$$o = F_H \tag{7}$$

Given that the mechanism moves in an extensive range of angles and moves from the first to the third quadrant of the coordinate system, attention must be paid to the sign of the force value. The movement of the hydraulic cylinder, i.e. its retracting or extraction, defines the direction of the force created by the hydraulic cylinder. Depending on the direction of movement of the hydraulic cylinder, the sign of the force value calculated by Eq. (6) changes.

An integral part of the objective function is the penalty function, which avoids those solutions that are not realistically feasible in obtaining the results of the optimisation variables.

4.2. Limits of searching

For the optimisation results to be used in real life, the limit values of the optimisation variables must be defined. In this paper, the optimisation of nine variables representing three different types of dimensions is carried out. Those optimisation variables are the length of the mechanism L1, L2, L3 and L4 levers, the angle η, and the coordinates of the compound lever and hydraulic cylinder supports. The order of optimisation variables is shown in Eq. (8).

$$OV = [L_1, L_2, L_3, L_4, \eta, X_D, Y_D, X_F, Y_F] \tag{8}$$

The numerical values of the lower and upper limits of the optimisation variables are given by Eq. (9) and Eq. (10).

$$LB = [300{,}300{,}300{,}300{,}50{,}200{,}-400{,}1000-400] \tag{9}$$

$$UB = [1500{,}1500{,}1500{,}1500{,}160{,}1000{,}0{,}1600{,}0] \tag{10}$$

4.3. Constraints

In addition to the limit values of the variables, defining the limitations also plays a significant role in shaping the solution at the end of the optimisation procedure. The constraints used in the optimisation process are described in detail in the paper [3] and are not presented in this paper. The constraints that are introduced into the mathematical model are used when defining the objective function, which was mentioned earlier. In this case, the limitations primarily refer to avoiding obtaining structurally impossible solutions. In this case, the constraints primarily refer to avoiding obtaining structurally impossible solutions, such as a solution involving encroaching one element into another element or vehicle chassis.

The constraints used in the optimisation procedure refer to the positions of the members of the mechanism at the beginning of the movement, i.e. in the initial position, during the movement of the ramp, as well as at the end of the movement of the ramp, i.e. in the final position.

One of the crucial constraints is the limitation of the stroke of the hydraulic cylinder, which, in addition to not having an enormous value, must not have a value greater than the initial length of the hydraulic cylinder, i.e. the length of the fully retracted hydraulic cylinder.

5 RESULTS AND DISCUSSION

The authors of the original papers provided the source code for used optimisation algorithms [10-13]. They were all adjusted and configured in the following way:

- T=1000 – the total number of completed iterations;
- N=60 – the number of searching agents;
- dim=9 – the problem's dimension corresponding to the number of optimised variables.

The number of searching agents for the SAR algorithm was changed to correspond to recommendations from the paper [13], where it was stated that the optimal number of searching agents equals double the number of optimised variables, so in this case, it equals 18.

All four algorithms were run 100 times each, and the values of the objective functions obtained through the optimisations are presented in the form of the box diagrams in Fig. 10.

It can be seen that the best values were obtained using SAR and SDO optimisation algorithms, where the objective function values within 100 optimisation runs are the lowest and the most consistent, meaning that these two algorithms have a higher chance of reaching the best solution. SMA also reaches consistent values of the objective function through 100 runs. However, these values are considerably worse compared to the other three algorithms.

In Fig. 11, oscillations of the obtained values of the objective function per run of SAR, SDO and MPA algorithms were given. These diagrams show how the value of the objective function can differ from run to run of the optimisation.

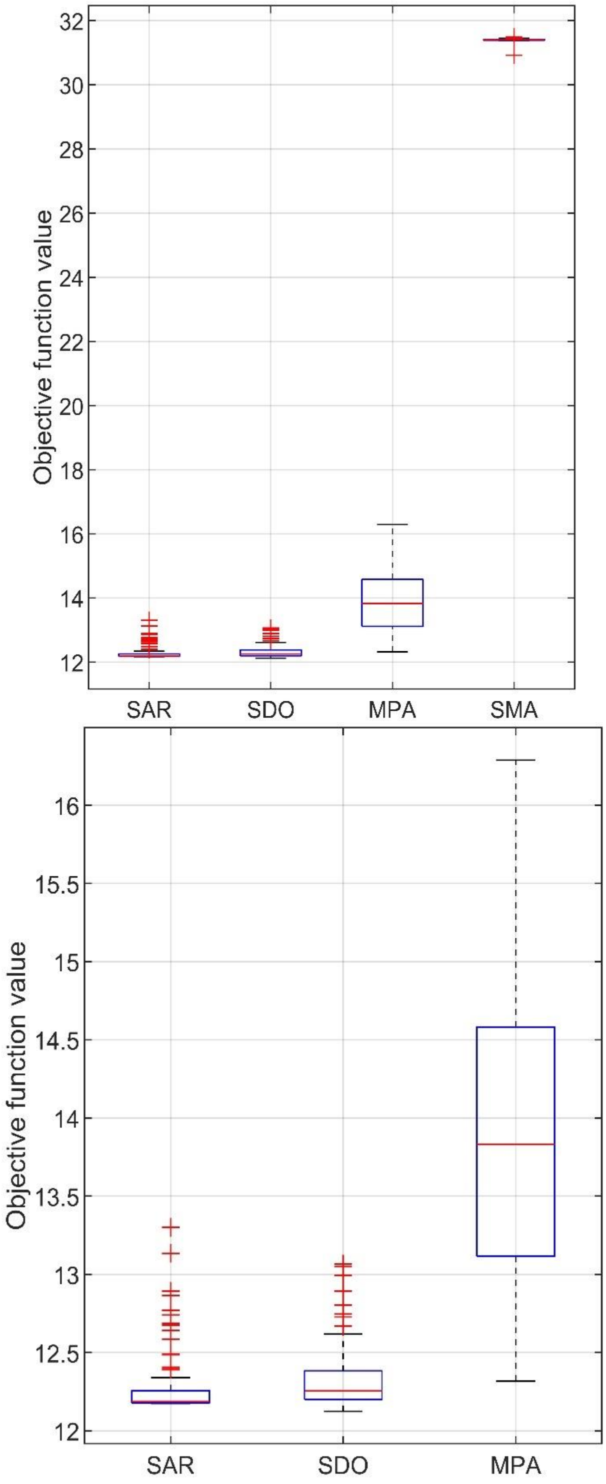

Fig. 10 *Box diagrams for SAR, SDO, MPA and SMA algorithms run 100 times*

Table 3 The optimisation results after 100 runs per optimisation algorithm

Algorithm	F(x)	STD	%
MPA	12.31850344	0.907375139	1.577088179
SAR	12.17457752	0.207939632	0.41354814
SDO	12.12422978	0.196752116	0
SMA	30.9252364	0.053679695	60.79502958

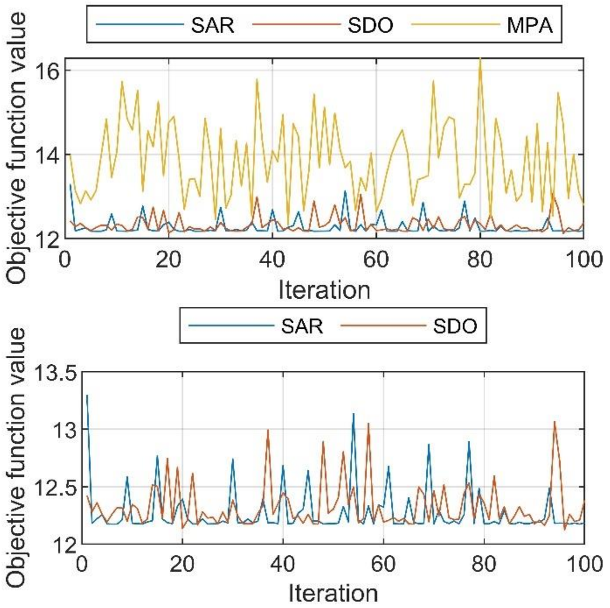

Fig. 11 Oscilaction of the best obtained value through the optimisation runs

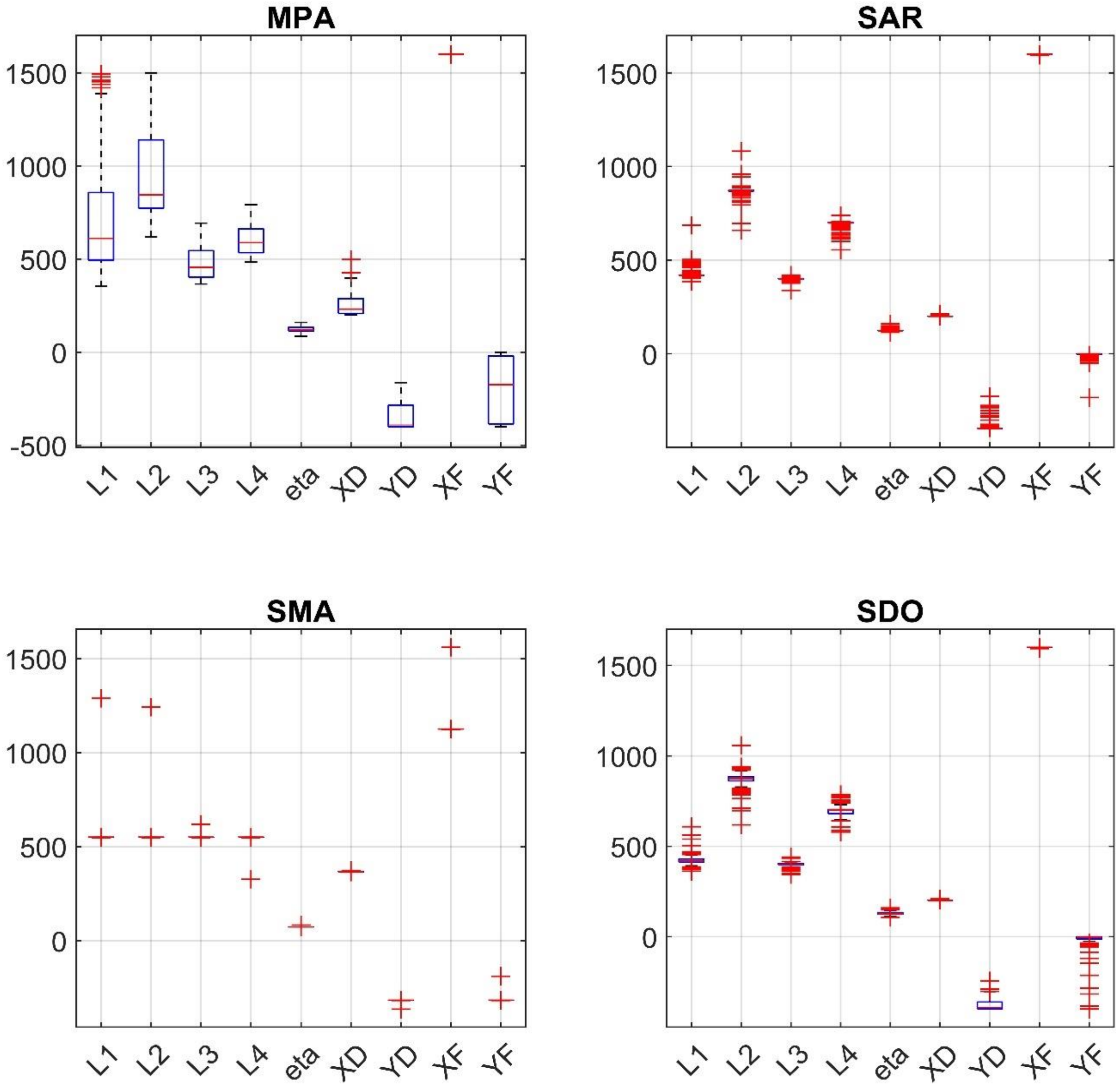

Fig. 12 Searched space of the variable values for the 100 best solutions for each algorithm

Table 4 The best optimised variable values after 100 runs per algorithm, for each of the algorithms

	L1	L2	L3	L4	eta	XD	YD	XF	YF
MPA	372.76533	839.58542	391.430613	764.028252	136.30288	200.000216	-399.564284	1599.999	-391.84988
SAR	418.78334	872.43987	400.303771	700.513773	123.417377	200.00140	-399.999994	1599.999	-0.0035154
SDO	377.01294	887.03806	408.864139	777.970230	142.438766	200.14530	-390.989588	1599.892	-399.58099
SMA	1288.2427	1241.3005	618.07500	326.593734	82.561578	372.699438	-363.739392	1559.449	-188.98117

Table 3 shows the best-obtained values of the objective function after 100 runs per algorithm and the standard deviation of the best value through the 100 runs. It can be seen that the best value of the objective function equals 12,12422978, and it was obtained using the SDO optimisation algorithm.

The next best value was obtained using the SAR optimisation algorithm, and the difference between the value obtained with SDO and SAR equals 0,41%. The SDO has a lower standard deviation compared to SAR as well. The SMA optimisation algorithm presents the lowest standard deviation; however, this algorithm obtains the worst objective function value, which is 60,7% higher compared to the one obtained using the SDO optimisation algorithm.

This is also represented in Fig. 10, where the box diagram for the SMA algorithm takes the smallest amount of space compared to the others. However, it is positioned higher on the scale. The worst standard deviation through 100 algorithm runs is present with the MPA optimisation algorithm, which gives its best solution, which is 1,58% higher than the SDO.

In Fig. 12, the values of optimised variables for the best solution for each of the 100 runs per algorithm were visualised. It can be seen that the higher standard deviation through the optimisation runs means a more significant number of different solutions in different areas of the search space. For example, it can be noted that the SMA algorithm mostly picks the same values of the optimised variables as the best solutions as the objective function converges to the best solution. On the other hand, the SDO algorithm gives a more extensive variety of optimal solutions through different optimisation runs. This behaviour implies that if the algorithm is run only a few times, the best solution the SDO algorithm can reach might not be reached. However, every solution the SDO algorithm gives as the best solution per run is better than the best solution obtained using SMA.

Despite the excellent performance of the MPA optimisation algorithm seen in the literature [14-15], this algorithm did not prove efficient, especially considering Fig. 11, where it can be seen that most of the obtained values in 100 runs are higher compared to those obtained in any run of the SDO and SAR optimisation algorithms.

The optimal value obtained by each of the algorithms, considering all 100 runs, is displayed in Table 4. The solution obtained with the SDO algorithm, with the objective function value equal to 12,12422978 kN, is illustrated in Fig. 13.

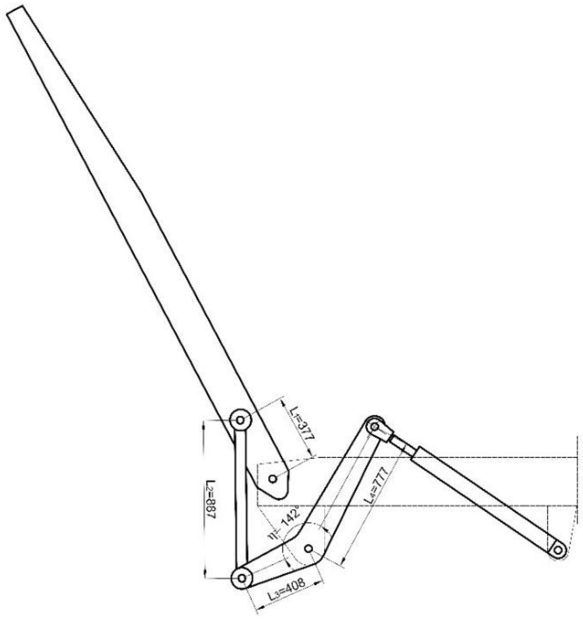

Fig. 13 *Illustration of the optimal solution*

The hydraulic-cylinder force change diagram for the optimal solution highlighted in Table 4 is given in Fig. 14.

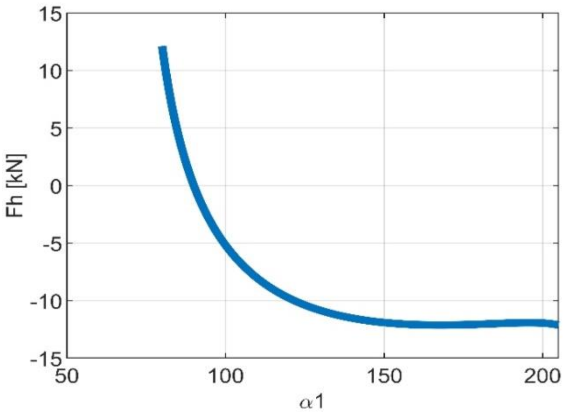

Fig. 14

Hydraulic-cylinder force change

6 CONCLUSION

The choice of the optimisation algorithm for the specific engineering problem, such as the heavy-weight loading ramp mechanism optimisation, can significantly impact the optimisation result. Even though some optimisation algorithms perform better on other optimisation problems and benchmark examples, this behaviour does not always convey to every engineering problem, confirming the conclusions from the [5-6]. The most commonly used functions for benchmarking the optimisation algorithms can be misleading, especially knowing that some of the optimisation algorithms contain certain biases towards them, which is investigated in [16] which implies that more research is needed to find benchmark functions that could be used for testing these algorithms on realistic engineering problems.

The results show that the difference between the best values obtained with different optimisation values can be as high as 60%. The random nature of the metaheuristic algorithms means that a different solution can be reached with each run. The new solution can be better or worse. Different algorithms have lower differences between the reached solutions through runs. For this problem of finding the optimal design parameters for the heavy-weight loading ramp mechanism, the SDO and SAR optimisation algorithms proved to be adequate, giving the optimal solution with slight variations between the optimisation runs.

With this in mind, it was proven that the metaheuristic optimisation algorithms can be successfully utilised in the mechanism synthesis process and can significantly improve the performance of a mechanism such as the one for a heavy-weight loading ramp.

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Contact address:
Predrag Mladenović
University of Kragujevac
Faculty of Mechanical and Civil Engineering in Kraljevo
36000 Kraljevo
Dositejeva 19,
E-mail: mladenovic.p@mfkv.kg.ac.rs