Application of Water Cycle Algorithm on Ramshorn Hook Optimization Problem

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This research presents the problem of optimization of the most critical cross-sectional area of Ramshorn hook, where the geometric parameters of the trapezoidal and T cross-sections were taken as optimization variables. The minimization of the area of the cross-section of the Ramshorn hook was set as the main goal in this research. The stresses at the inner and outer fibers of the hook cross-section were taken according to the DIN standard, and they represented the constraint functions for the optimization model.

As a method of optimization, two nature-inspired metaheuristic algorithms were applied for this optimization problem, using MATLAB software: Water Cycle Algorithm (WCA) and its modified version Evaporation Rate based Water Cycle Algorithm (ER-WCA). The optimization results for both types of cross-sections were compared to show which one achieves the best results. The comparison of the applied optimization algorithms was performed, too.

Keywords: Ramshorn hook, Optimization, Water cycle algorithm, Evaporation rate based water cycle algorithm

1. INTRODUCTION

Ramshorn hook is a very important component for lifting and hanging of heavy load capacities for heavy-duty cranes and the marine industry. Ramshorn hook should be designed and manufactured in such a way that it delivers the best performance under all working conditions without function cancellation, failure and accident. The failure depends on various factors such as material properties, geometry and overload.

The design of a crane hook involves the determination of parameters such as type of material, the cross-sectional area, and shape, the radius of curvature, etc. For this reason, the problem of analysis and optimization design of a crane hook is the subject of research in many publications.

The analysis of these types of equipment is mainly done by applying FEM. In the paper [1], an analysis of one standard hoist hook with a capacity of 20 tons was carried out using Autodesk Simulation software. The paper [2] presents the FEM analysis of Ramshorn hook using ANSYS software package, where a comparison of circular cross-section with T and I cross-sections was performed.

In the research [3], the design of a hoisting mechanism of an EOT crane is presented, with the FEM analysis of the crane hook in the ANSYS software package. The cross-section of one standard hook was modified, and other different cross-sectional shapes were also observed, such as circular, square, trapezoidal and triangular cross-sections. In the paper [4], the design and validation of the hook with T cross-section, used in double spring balancers are given. CREO and ANSYS software packages were used for the 3D model and FEM analysis.

Recently, laminated crane hooks have become increasingly used. The review paper [5] gives an overview of the literature about the design, analysis and optimization of this type of equipment.

The paper [6] presents an analysis of the fracture of a hook-shaped steel rod from a lifting beam, resulting from the torsional overload of the hook body, where microstructural, fractographic, and strength evaluation were used as analytical techniques.

In addition to FEM, analysis can also be done analytically. In the paper [7], the stresses at the characteristic points of the critical cross-section of one standard crane hook were calculated using an approximate method and using two exact methods, where these values were compared with the critical stresses according to DIN standard. The recommendations are given in the case where the stresses are calculated by an approximate method.

Numerical optimization methods are of great use for engineering problems, especially metaheuristic optimization algorithms. In the paper [8], the optimization of different cross-sections of a crane hook was performed using several metaheuristic algorithms. In the paper [9], the optimization and comparison for two cases of T and I cross-sections of a crane hook were performed, using two physics-inspired optimization algorithms.

Based on the above publications, it can be seen the importance of the analysis and optimization of these types of equipment. This research will be carried out the optimization of the trapezoidal cross-section of Ramshorn hook, as well as T cross-section of one standard hook capacity. It also will be carried out and a comparison of results for both cross-sections.

2. OPTIMIZATION PROBLEM

2.1. Optimization model:

The next figure shows one standard Ramshorn hook, according to [11], as well as the static model for calculation (Fig. 1).

Also, Fig. 1 shows the critical place (*A–A*) where the analysis and optimization of the cross-section are performed, which is the topic of this research.

The goal of the research for this optimization problem is to minimize the objective function (cross-sectional area) subjecting the constraint functions, which are composed of critical stresses.

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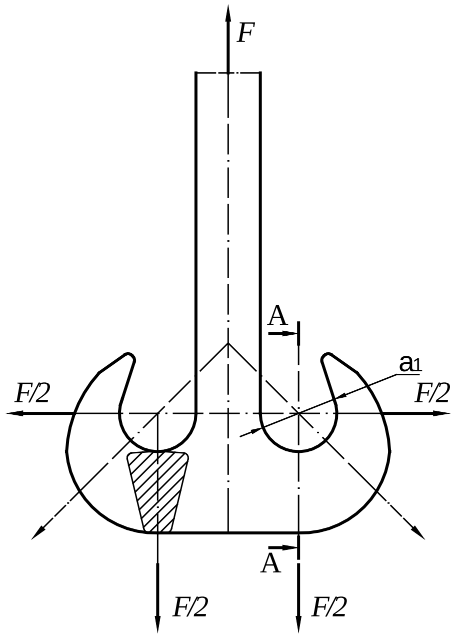

Figure 1: Ramshorn hook

The mathematical formulation of the objective function is:

$$f(X) = A(X) = A(x_1 \; ... \; x_n)\,, \tag{1}$$

where the parameters from x_1 to x_n present the optimization variables.

The input parameters for this optimization problem are:

F - the lifting force, according to [10],

a_1 - inner diameter (Fig. 1), according to [11],

$\sigma_{z,g}$, $\sigma_{d,g}$ - critical stresses, according to [10].

Below will be present the objective functions for both profiles and the constraint functions.

2.2. Objective function for trapezoidal cross-section:

The objective function is represented by the area of trapezoidal cross-section of Ramshorn hook at the most critical location (*A – A*, Fig. 1).

The cross-sectional area (Fig. 2), the objective function, is:

$$A = A_{tr} = \frac{b_1 + b_2}{2} \cdot h \tag{2}$$

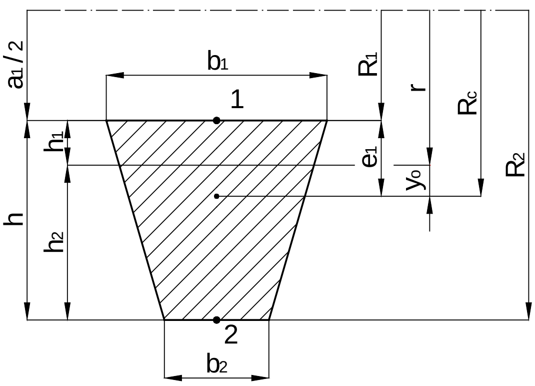

Figure 2: Trapezoidal cross-section

The previous figure shows the geometric relationships between parameters that are required for the calculation, where:

e_1 - the position of the center of the cross-section (Fig. 2),

R_1 - the radius of inner fiber (Fig. 2),

R_2 - the radius of outer fiber (Fig. 2),

R_c - the radius of the centroidal axis (Fig. 2),

r - the radius of the neutral axis (Fig. 2),

y_o - the distance between the centroidal axis and the neutral axis (Fig. 2).

Other geometrical parameters and variables that are the subject of optimization, are shown in Fig. 2.

The radius of the neutral axis is defined in the following way, (3) and (4):

$$r = \frac{A_{tr}}{\int\limits_{A_{tr}} \frac{dA}{\rho}} \tag{3}$$

$$\int\limits_{A_{tr}} \frac{dA}{\rho} = b_1 \cdot \left(e_o + \frac{a_1 + 2 \cdot h}{2} \cdot \frac{1 - e_o}{h} \right) \cdot \ln \frac{a_1 + 2 \cdot h}{a_1} - \\ -b_1 \cdot (1 - e_o), \; e_o = b_2 / b_1 \tag{4}$$

2.3. Objective function for T cross-section:

The objective function is represented by the area of T cross-section of Ramshorn hook at the most critical location (*A – A*, Fig. 1).

The cross-sectional area (Fig. 3), the objective function, is:

$$A = A_T = b \cdot t + h \cdot s \tag{5}$$

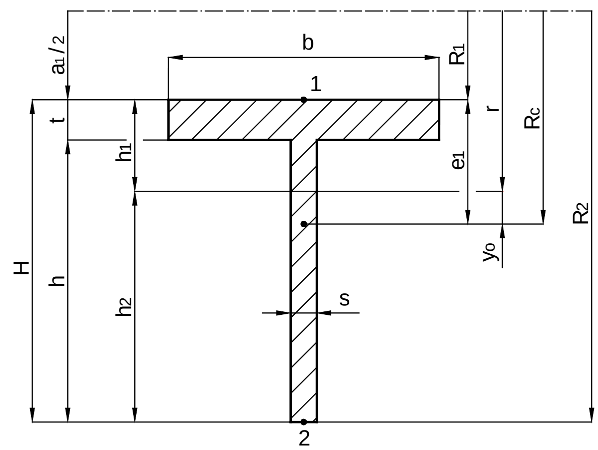

Figure 3: T cross-section

The previous figure shows the geometric relationships between parameters that are required for the calculation, and their meaning is the same as in the previous case.

The radius of neutral axis is defined in following way, (6) and (7):

$$r = \frac{A_T}{\int\limits_{A_T} \frac{dA}{\rho}} \tag{6}$$

$$\int\limits_{A_T} \frac{dA}{\rho} = b \cdot \ln \frac{a_1 + 2 \cdot t}{a_1} + s \cdot \ln \frac{a_1 + 2 \cdot (h + t)}{a_1 + 2 \cdot t} \tag{7}$$

2.4. Constraint functions:

The optimization process is based on critical stresses, according to [10], where crane hook is treated as a curved beam.

The maximum values for normal stresses in the characteristic points (point 1 and point 2, Fig. 2 and Fig. 3) are:

$$\sigma_z = \frac{F}{2 \cdot A} + \frac{M}{S_x} \cdot \frac{h_1}{R_1} \tag{8}$$

and

$$\sigma_d = \frac{F}{2 \cdot A} - \frac{M}{S_x} \cdot \frac{h_2}{R_2} \tag{9}$$

$$M = \frac{F}{2} \cdot R_c \tag{10}$$

$$S_x = A \cdot y_o \tag{11}$$

where:

M - the bending moment,

S_x - the static moment of the area.

The maximum values for shear stress is:

$$\tau = \frac{F}{2 \cdot A} \tag{12}$$

Finally, the mathematical formulation of the constrain functions are:

$$g_1 = \sigma_1 = \sqrt{\sigma_z^{\,2} + 3 \cdot \tau^2} \le \sigma_{z,g} \tag{13}$$

and

$$g_2 = \sigma_2 = \sqrt{\sigma_d^{\,2} + 3 \cdot \tau^2} \le \sigma_{d,g} \tag{14}$$

Also, this analysis is adopted that the minimum value of the thickness of the profile is *0.5 cm* (for T cross-section).

3. APPLIED OPTIMIZATION ALGORITHMS

In this paper, the optimization procedure was performed using two metaheuristic algorithms based on nature: Water Cycle Algorithm (WCA) and its modified version Evaporation Rate based Water Cycle Algorithm (ER-WCA). Both algorithms are simulated in the MATLAB software.

The Water Cycle Algorithm (WCA) as an optimization method is introduced in [12]. The fundamental concepts and ideas which underlie the WCA are inspired by nature and based on the observation of the water cycle process and how rivers and streams flow to a sea in the real world. Similarly to other metaheuristic algorithms, the proposed method begins with an initial population, the so-called raindrops. The best individual (best raindrop) is chosen as a sea. Then, a number of good raindrops are chosen as a river and the rest of raindrops are considered as streams which flow to the rivers and the sea. The paper [13] provides a detailed open source code for the WCA, of which the performance and efficiency has been demonstrated for solving engineering constrained optimization problems.

The Evaporation Rate based Water Cycle Algorithm (ER-WCA) is a modified version of the WCA, [14]. In order to define this concept, in the ER-WCA, the evaporation process is modified by adding the concept of evaporation rate, which offers improvement in search. Furthermore, the evaporation condition is also applied for the streams that directly flow to the sea based on the new approach. The ER-WCA shows a better balance between exploration and exploitation phases compared to the standard WCA. The ER-WCA was able to find the global minimum in multi-criteria optimization problems with a minimum possibility of getting trapped in the local minimum.

The source codes for both algorithms are present on the website [15].

4. OPTIMIZATION RESULTS

The optimization process was performed using the mentioned algorithms WCA and ER-WCA. The source codes were taken from the website [15], written for MATLAB software.

The optimization variables are b_1, h, and b_2 for trapezoidal cross-section (Fig. 2) and b, t, h and s, for T cross-section (Fig. 3). Input parameters for optimization, according to [10] are: $F=80\ kN$ (for the hook capacity: $Q=8\ t$, drive group: 3m, strength class: S) and $a_1=6.3\ cm$. The permissible stresses are taken according to [10], and their values are: $\sigma_{z,g}=15\ kN/cm^2$ – tensile critical stress and $\sigma_{d,g}=6.3\ kN/cm^2$ – compressive critical stress.

The cross-sectional area of standard crane hook [11], in comparison to which the optimal results are compared is: $A_s=24.857\ cm^2$. Some geometrical constraints (height and width) were taken, too.

For both algorithms, population size is: 200, number of rivers+sea: 4 and number of iterations: 1000 (control parameters for optimization).

The following tables show the results of optimization for trapezoidal cross-section (optimal cross-sectional geometric parameters and areas, convergence characteristics and savings in material) for both algorithms, (Table 1÷Table 3).

Table 1: Results of optimization for trapezoidal cross-section

Method	WCA	ER-WCA
b_1 (cm)	2.641352	2.645896
h (cm)	15.243012	15.216829
b_2 (cm)	0	0
time (s)	**13.848421**	16.549830
Best (cm^2)	**20.131**	**20.131**
Mean (cm^2)	20.148	**20.134**
Worst (cm^2)	27.668	**21.842**
Std	0.324	**0.057**
Saving (%)	19.01	19.01

Table 2: Results of optimization for trapezoidal cross-section with constraint (H_{max}=6.7 cm)

Method	WCA	ER-WCA
b_1 (cm)	4.616152	4.616152
h (cm)	6.7	6.699999
b_2 (cm)	2.678085	2.678086
time (s)	**14.078390**	14.361893
Best (cm^2)	**24.436**	**24.436**
Mean (cm^2)	**24.445**	24.458
Worst (cm^2)	**27.290**	32.798
Std	**0.141**	0.318
Saving (%)	1.69	1.69

Table 3: Results of optimization for trapezoidal cross-section with constraint (H_{max}=10 cm)

Method	WCA	ER-WCA
b_1 (cm)	3.454282	3.454283
h (cm)	10	10
b_2 (cm)	0.776428	0.776428
time (s)	16.587225	**16.122742**
Best (cm^2)	**21.154**	**21.154**
Mean (cm^2)	21.167	**21.157**
Worst (cm^2)	25.513	**23.850**
Std	0.233	**0.086**
Saving (%)	14.90	14.90

The following tables show the results of optimization for T cross-section (optimal cross-sectional geometric parameters and areas, convergence characteristics and savings in material) for both algorithms, (Table 4÷Table 7).

Table 4: Results of optimization for T cross-section

Method	WCA	ER-WCA
b (cm)	6.070106	6.070106
t (cm)	0.5	0.5
h (cm)	18.978059	18.978059
s (cm)	0.5	0.5
time (s)	17.216509	**15.875222**
Best (cm^2)	**12.524**	**12.524**
Mean (cm^2)	12.558	**12.543**
Worst (cm^2)	30.619	**26.777**
Std	0.685	**0.458**
Saving (%)	49.62	49.62

Table 5: Results of optimization for T cross-section with constraint (H_{max}=6.7 cm)

Method	WCA	ER-WCA
b (cm)	11.340956	11.339729
t (cm)	0.5	0.5
h (cm)	6.2	6.2
s (cm)	2.405889	2.405988
time (s)	18.525694	**16.721073**
Best (cm^2)	**20.587**	**20.587**
Mean (cm^2)	20.967	**20.648**
Worst (cm^2)	**32.519**	44.314
Std	1.562	**1.025**
Saving (%)	17.18	17.18

Table 6: Results of optimization T cross-section with constraints (b_{max}, H_{max}=6.7 cm)

Method	WCA	ER-WCA
b (cm)	6.7	6.7
t (cm)	0.607912	0.588040
h (cm)	6.092088	6.111960
s (cm)	2.821345	2.834086
time (s)	**15.932656**	16.322639
Best (cm^2)	**21.261**	21.262
Mean (cm^2)	**21.562**	21.568
Worst (cm^2)	33.245	**29.585**
Std	1.256	**1.236**
Saving (%)	14.47	14.46

Table 7: Results of optimization for T cross-section with constraint (H_{max}=10 cm)

Method	WCA	ER-WCA
b (cm)	9.276761	9.176871
t (cm)	0.5	0.5
h (cm)	9.5	9.5
s (cm)	1.189075	1.194284
time (s)	18.112465	**16.886159**
Best (cm^2)	15.935	**15.934**
Mean (cm^2)	16.012	**15.950**
Worst (cm^2)	31.315	**22.507**
Std	0.680	**0.281**
Saving (%)	35.89	35.90

The following figures show the convergence diagrams for the mentioned methods of optimization and cross-sectional types (Fig. 4÷Fig. 10).

5. CONCLUSION

It can be noted that the optimization task was successfully realized, as can be seen from the values of savings in material, shown in the previous tables (Table 1÷Table 7). In this case, a saving of 19% was achieved for trapezoidal cross-section, while for T cross-section, savings of as much as 49% were achieved.

For both types of cross-section profiles, the optimum height values are significantly higher than the standard height (6.7 cm) for the observed example (Table 1 and Table 4). In the case of the trapezoidal cross-section, for optimal geometric values, a triangular cross-section was obtained (Table 1). For this reason, additional geometric constraints are included.

With the height restriction (H_{max}=6.7 cm), for the trapezoidal cross-section, very small savings are obtained (Table 2), which means that the standard hook for the observed example is designed optimally since the cross-section of the standard hook is a trapezoidal shape. With increasing height (H_{max}=10 cm), the value of the optimum cross-sectional area decreases (Table 3).

In the case of T cross-section, with height restriction (H_{max}=6.7 cm), an enviable value of material savings was achieved, but the width of the profile base was much larger (Table 5). For this reason, the width restriction of the profile base was also observed, so that there was a slight increase in the optimum cross-sectional area, which was expected (Table 6). With increasing height (H_{max}=10 cm), the value of the optimum cross-sectional area decreases (Table 7). Finally, it should be noted that this cross-sectional shape gives a much lower value of the optimum cross-sectional area in comparison to the trapezoidal cross-section.

Regarding the applied optimization algorithms, it should be said that in most cases both algorithms gave the same values of optimal surfaces. In most cases, the ER-WCA algorithm achieves better values of the convergence diagram parameters, and especially for the standard deviation value (Table 1÷Table 7).

Regarding the time it takes to perform the optimization process, in some cases the first optimization method performed better time, and in some cases the second method (Table 1÷Table 7).

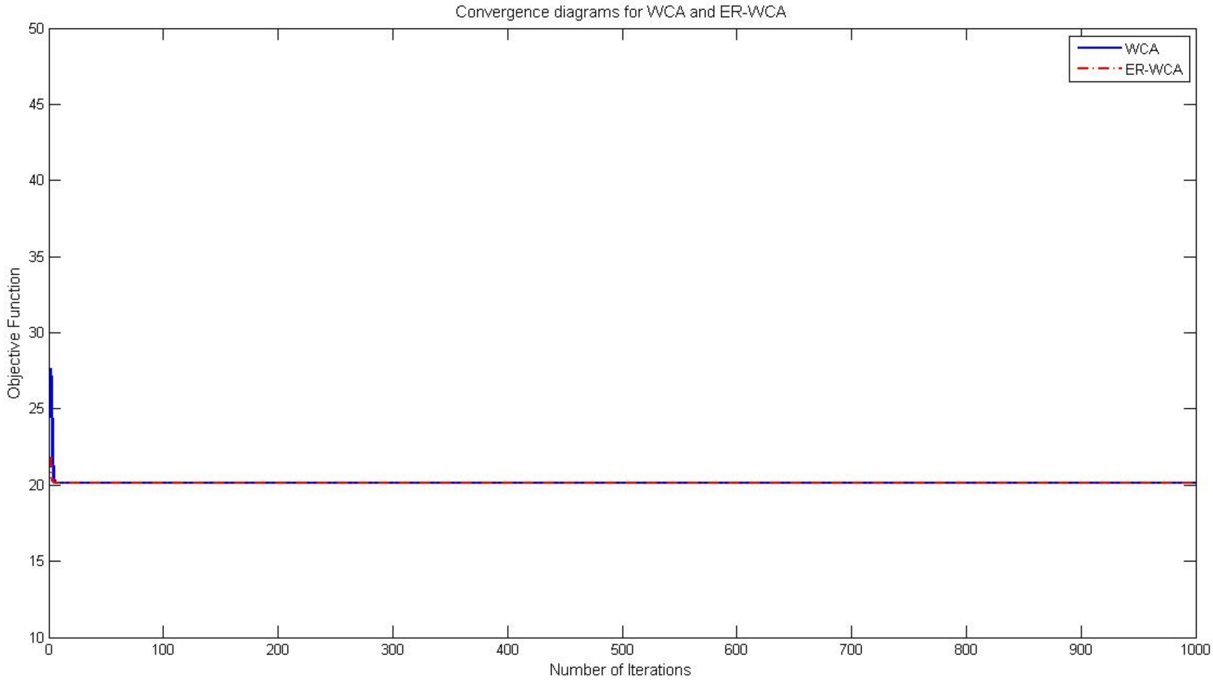

Figure 4: Convergence diagrams for trapezoidal cross-section

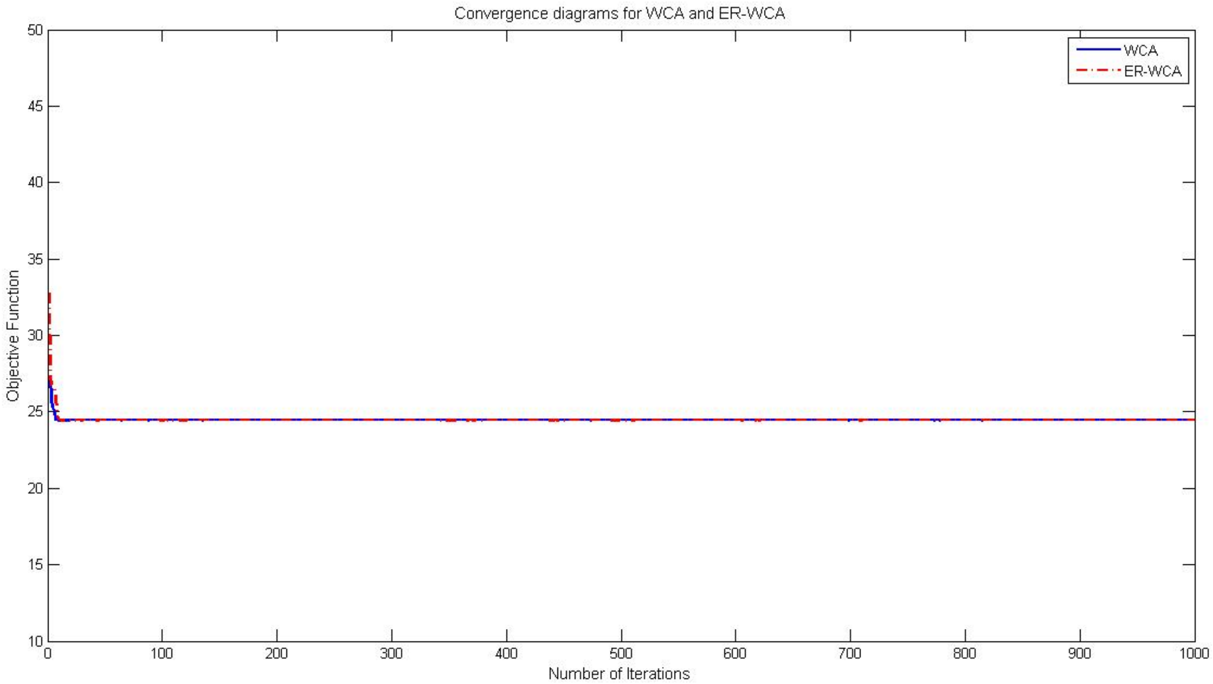

Figure 5: Convergence diagrams for trapezoidal cross-section with constraint (H_{max}=6.7 cm)

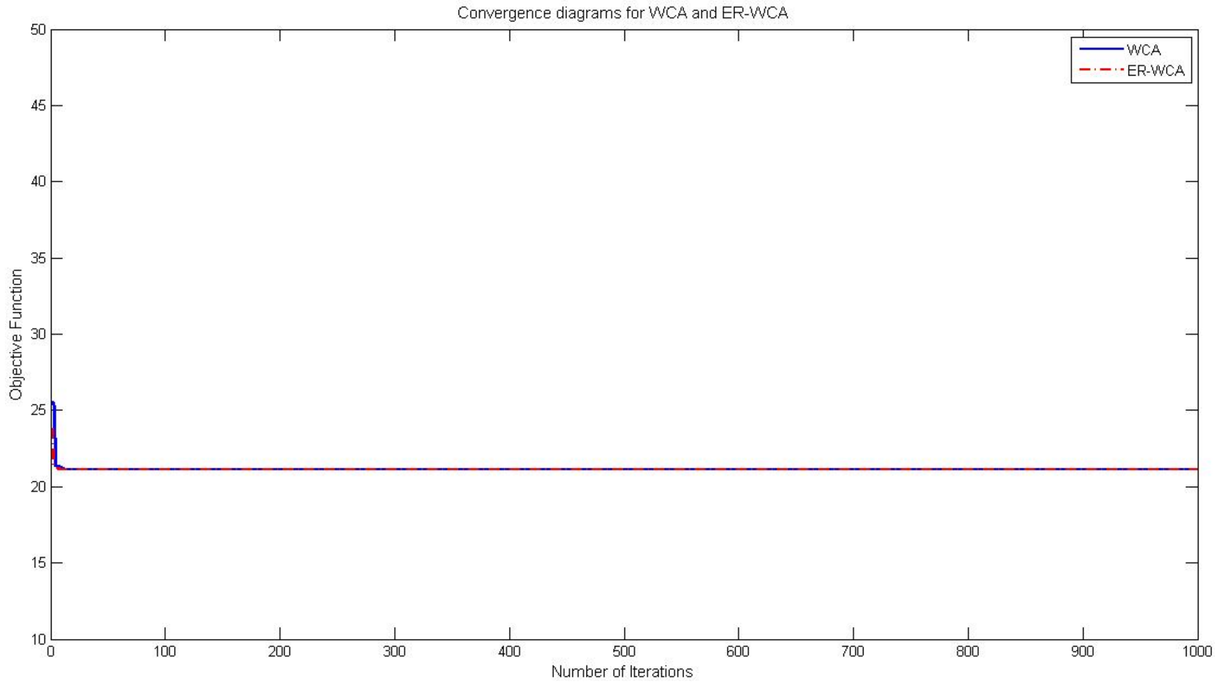

Figure 6: Convergence diagrams for trapezoidal cross-section with constraint (H_{max}=10 cm)

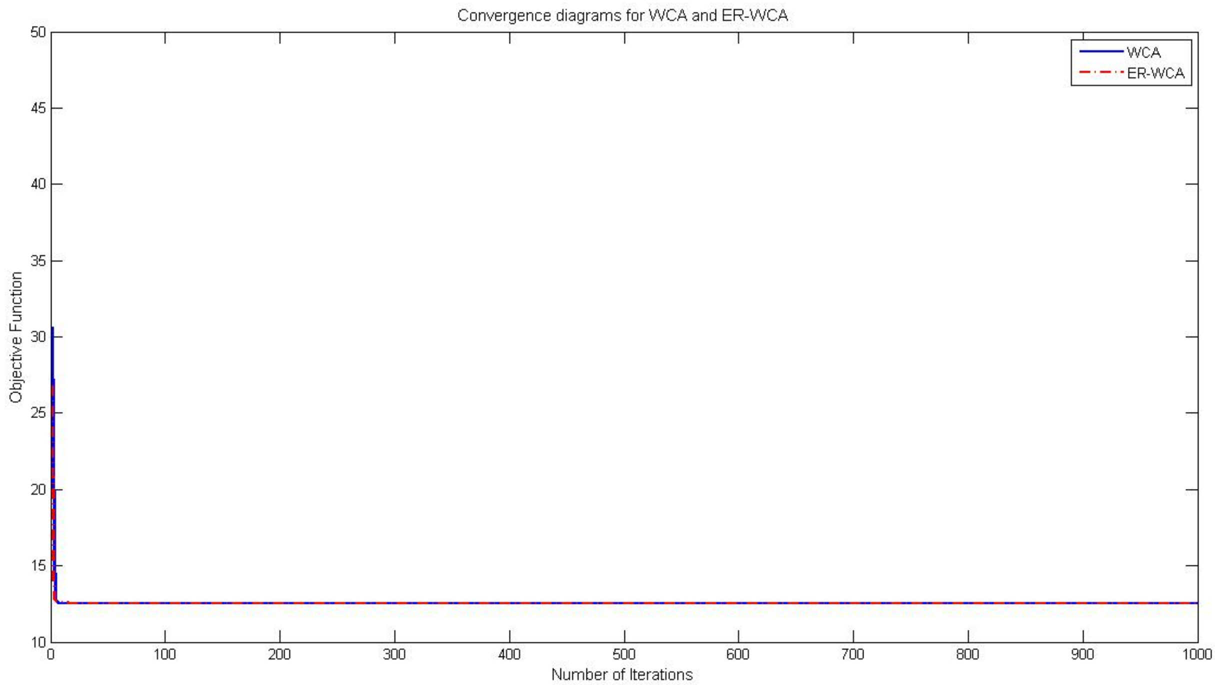

Figure 7: Convergence diagrams for T cross-section

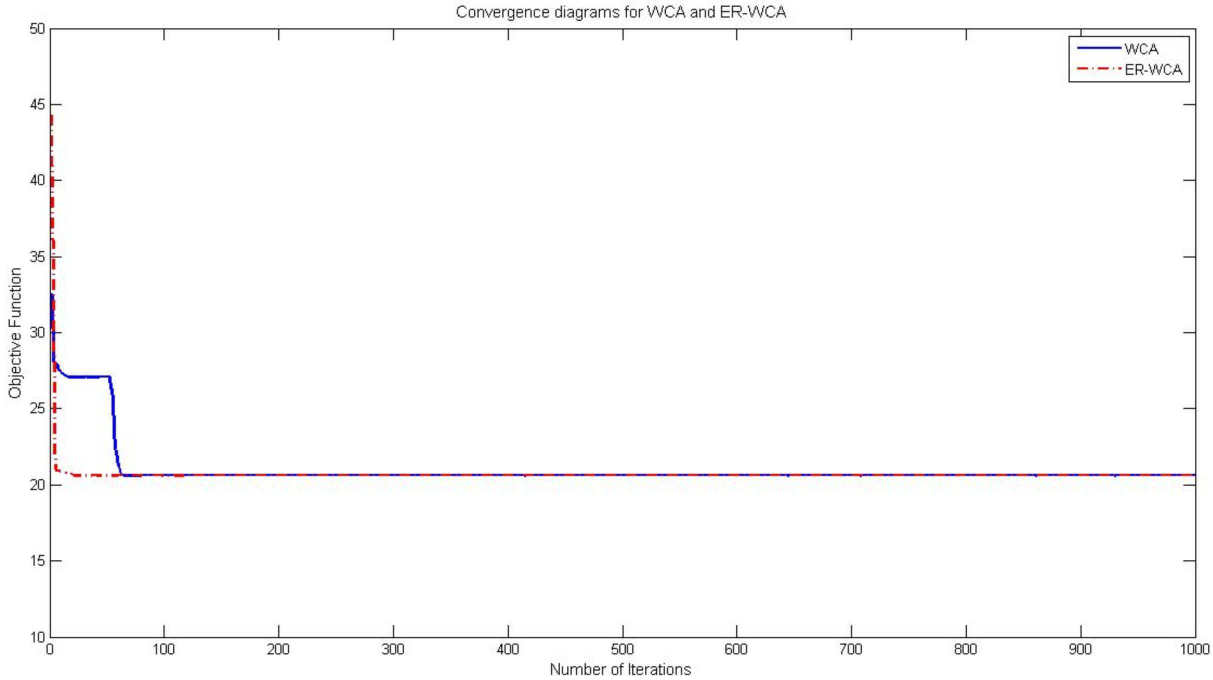

Figure 8: Convergence diagrams for T cross-section with constraint (H_{max}=6.7 cm)

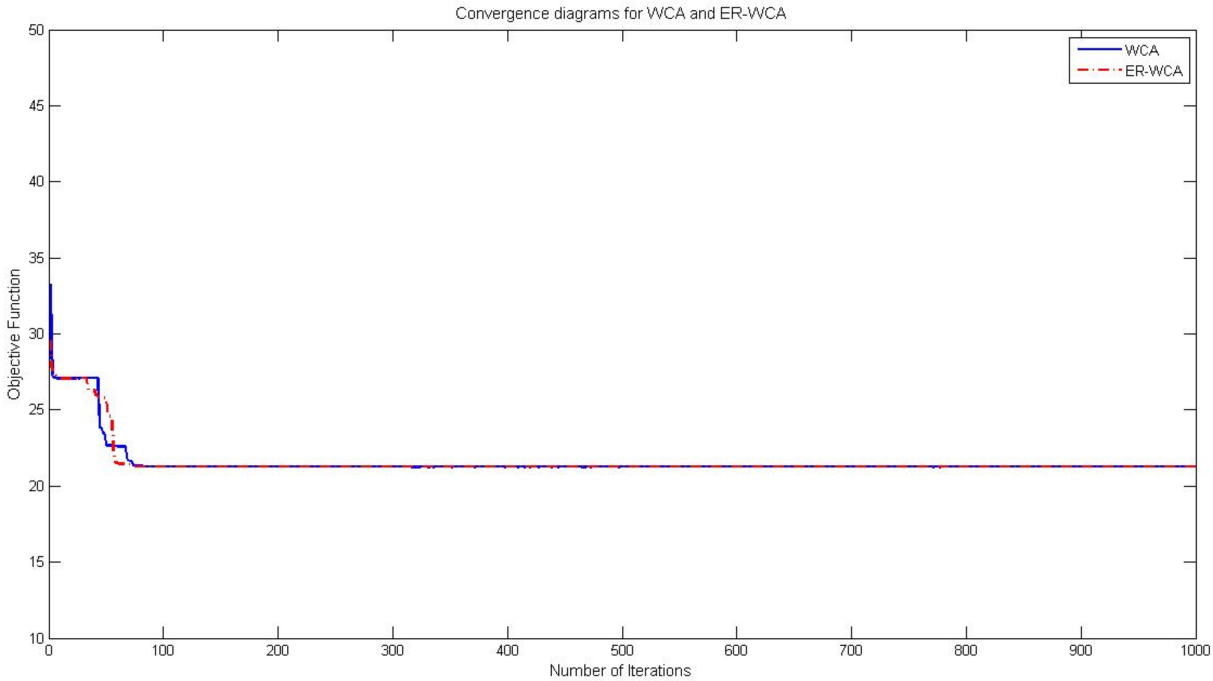

Figure 9: Convergence diagrams for T cross-section with constraints (b_{max}, H_{max}=6.7 cm)

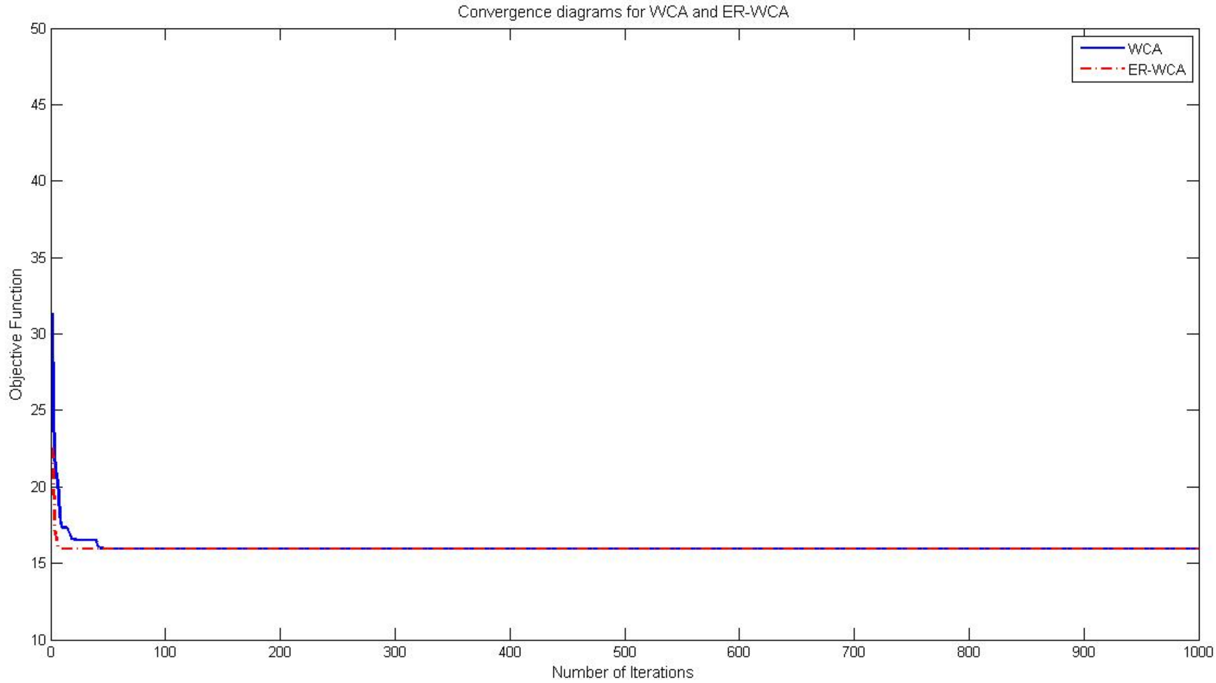

Figure 10: Convergence diagrams for T cross-section with constraint (H_{max}=10 cm)

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