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# Komparativna analiza i optimizacija T i I poprečnih preseka dizalične kuke primenom dva algoritma inspirisana fizikom

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*U ovom radu predstavljene su analiza i optimizacija geometrijskih parametara T i I poprečnih preseka dizalične kuke, posmatrane za najkritičnije mesto konstrukcije kuke. Smanjenje površine poprečnog preseka dizalične kuke postavljeno je kao glavni cilj u ovom istraživanju. Kao funkcije ograničenja posmatraju se naponi u karakterističnim tačkama najkritičnijeg poprečnog preseka, sračunati prema Vinkler-Bakovoj teoriji, a takođe su postavljeni i određeni geometrijski uslovi. Za metode optimizacije izabrana su dva metaheuristička algoritma zasnovana na zakonima fizike, algoritam pretrage naelektrisanja sistema (CSS) i algoritam razmene toplote (TEO), korišćenjem MATLAB softverskog paketa. Osnovni cilj istraživanja je da se pokaže da predloženi poprečni preseci ostvaruju značajnu uštedu u odnosu na standardno izvođenje dizalične kuke, pri čemu je posmatrana jedna standardna nosivost. Oba posmatrana poprečna preseka su analizirana u dve varijante, pri čemu je izvršena i komparacija njihovih rezultata optimizacije, kako bi se pokazalo koja od njih ostvaruje najbolje rezultate. Takođe, izvršena je i komparacija primenjenih algoritama optimizacije.*

**Ključne reči: Dizalična kuka, Optimizacija, Metaheuristički algoritmi, MATLAB, Naponi**

## 1. UVOD

Dizalične kuke predstavljaju jako odgovorne komponente za vešanje i podizanje tereta velikih nosivosti. Manipulacija materijalom i opremom korišćenjem ovih tipova konstrukcija je prisutna kako na gradilištima i proizvodnim pogonima, tako i u raznim drugim industrijskih postrojenjima na poslovima održavanja i montaže.

Pravilnim korišćenjem ovih komponenti se može efikasno manipulisati teretima velike nosivosti, dok njeno nepravilno korišćenje, kao i nepravilan izbog može da dovode do otkaza funkcije, havarija i velikih nesreća. Dizajn dizalične kuke podrazumeva određivanje parametrima poput oblika i površine poprečnog preseka, materijala, radijusa zakrivljenosti itd. Iz ovog razloga je neophodno posvetiti pažnju pravilnim izborom oblika i geometrije poprečnog preseka dizalične kuke.

Zbog svoje odgovornosti i funkcija koje treba da obavlja, problem analize i optimizacije dizaličnih kuka je predmet istraživanja brojnih autora. Analiza dizalične kuke se vrši određivanjem naponskih stanja, a takođe i deformacija, za određene geometrijske karakteristike, pri čemu se najčešće primenjuje neki od softverskih paketa za MKE.

U radu [1] izvršena je MKE analiza jedne dizalične kuke primenom ANSYS softverskog paketa, pri čemu su date preporuke kako pripremiti model za ovu vrstu analize. 3D model kuke je dobijen primenom softverskog paketa Pro/Engineer. Određena je vrednost faktora sigurnosti za ovu vrstu konstrukcija. ANSYS je korišćen i u radovima [2] i [3]. U radu [2] istraživači su izvšili analizu jedne postojeće dizalične kuke, pri čemu su rezultate poredili sa analitičkim, kao i sa onim dobijenim u već objavljenim istraživanjima. U radu [3] autori vrše analizu dizaličnih kuka trapeznog i pravougaonog poprečnog preseka u cilju dobijanja optimalnih dimenzija koje će dati manje površine poprečnih preseka u odnosu na postojeća standardna rešenja. U ovoj analizi su posmatrani naponi i deformacije dizalične kuke.

Komparacija različitih oblika poprečnih preseka je vrlo česta tema u ovim istraživanjima. U radu [4] je izvršena komparacija različitih punih oblika poprečnih preseka korišćenjem ANSYS softverskog paketa. Slično prethodnom, u radu [5] izvršeno je poređenje poprečnog preseka jedne standardne kuke, sa modifikovanim oblikom trapeznim poprečnim presekom, kružnim poprečnim presekom i pravougaonim poprečnim presekom, pri čemu je naponska analiza izvršena korišćenjem ANSYS softverskog paketa, dok je 3D model pripremljen u CREO softverskom paketu. CREO je primenjen i u radu [6], gde je urađena modifikacija geometrije jedne dizalične kuke izrađene prema ANSI standardu.

Komparacija između T i I poprečnih presek dizalične kuke izvšena je u radu [7], gde su analitički rezultati poređeni sa onima dobijenim MKE analizom u ANSYS softverskom paketu. U radu [8] autori su primenom ANSYS softverskog paketa izvršili analizu jedne kuke sa dvostrukim krakom, pri čemu su poredili kružni poprečni presek sa T i I poprečnim presecima.

Kao što se može videti, T i I poprečni presek se sve više koriste kod analiza ovih vrsta konstrukcija. U radu [9] je izvršena komparativna analiza naponskih stanja za standardni trapezni poprečni presek konstrukcije kuke, kao i za T i I poprečni presek. Modeliranje ovih konstrukcija je izvršeno primenom softverskog paketa CATIA, a za analizu je korišćen ANSYS Workbench. U istraživanju [10] je izvršena optimizacija T poprečnog preseka dizalične kuke primenom različitih numeričkih metoda u softverskim paketima MATLAB i Ms EXCEL.

Numeričke metode optimizacije se sve češće primenjuju na inženjerskim problemima, a naročito metaheuristički algoritmi optimizacije. U radu [11] je primenom nekoliko metaheurističkih algoritama izvršena optimizacija trapeznog, elipsastog i T poprečni presek u

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MATLAB softverskom paketu, pri čemu su posmatrane određene standardne nosivosti.

Pored gore prikazanih poprečnih preseka dizaličnih kuka, mogu se analizirati svi potencijalni oblici koji mogu doći u obzir. U istraživanju [12] je pored tipičnih poprečnih preseka razmatran i parabolični poprečni presek. U radu [13] autori ukazuju na paradoks koji se javlja kod naponskih stanja u poprečnom preseku profila kuke, pri čemu se redukcijom površine poprečnog preseka na odgovarajućim mestima, odnosno izmenom oblika, može smanjiti vrednost ovih napona, uz smanjenje i njene površine.

Imajući u vidu sve gore navedeno, na značaj optimizacije, kao i dobijene rezultate u prikazanim istraživanjima, glavni cilj ovog rada je dobijanje optimalnih geometrijskih parametara T i I poprečnih preseka dizalične kuke, za jednu karakterističnu nosivost, na njenom najkritičnijem mestu, posmatrajući kuku kao krivolinijski štap. Takođe, izvršiće se i poređenje rezultata primenjenih metoda optimizacije.

## 2. PRIMENJENI ALGORITMI OPTIMIZACIJE

U ovom istraživanju optimizacija je izvršena primenom dva metaheuristička algoritama zasnovana na zakonima fizike: algoritam pretrage naelektrisanja sistema (CSS) i algoritam razmene toplote (TEO) - korišćenjem MATLAB softverskog paketa.

Algoritam pretrage naelektrisanja sistema (CSS) je predstavljen u radu [14], kao efikasan metaheuristički populacioni algoritam optimizacije, koji je inspirisan zakonima fizike. CSS koristi Kulonove zakone iz elektrostatike i Njutnove zakone mehanike. U ovom algoritmu svaki agent pretrage je naelektrisana čestica sa unapred određenim radijusom. Naboj čestica određuje se na osnovu njihovog kvaliteta. Svaka čestica stvara električno polje koje vrši dejstvo na druge naelektrisane objekte. Veličina rezultujuće sile određuje se korišćenjem zakona elektrostatike, a kvalitet kretanja određuje se upotrebom zakona Njutnove mehanike, [14].

Algoritam razmene toplote (TEO) je relativno novi metaheuristički populacioni algoritam optimizacije, koji je predstavljen u radu [15], i zasnovan je na Njutnovom zakonu hlađenja. Njutnov zakon hlađenja definiše da je stopa gubitka toplote tela proporcionalna razlici u temperaturi između tela i okoline. TEO svaku svoju česticu smatra objektom za hlađenje ili grejanje, a povezivanjem drugog agenta pretrage kao okolinu, između njih se događa prenos toplote i razmena toplotna. Nova temperatura objekta smatra se njegovom sledećom pozicijom u prostoru pretrage, [15].

MATLAB kodovi za oba posmatrana metaheuristička algoritma optimizacije, u svom izvornom obliku, bez modifikacija, su uzeti prema [16].

## 3. MATEMATIČKA FORMULACIJA OPTIMIZACIONOG PROBLEMA

Zadatak optimizacije kod ovog inženjerskog problema je određivanje optimalnih geometrijskih parametara za T i I poprečni presek konstrukcije dizalične kuke na njenom najkritičnijem delu, koji će dovesti do minimizacije njegove površine poprečnog preseka.

Optimizacioni problem se matematički definiše na sledeći način:

minimizacija funkcije cilja:

$$f(X) \quad (1)$$

u odnosu na funkcije ograničenja:

$$g_k(X) \le 0, \; k = 1,...,m \quad (2)$$

pri čemu je:

$$l_i \le X_i \le u_i, \; i = 1,...,n \quad (3)$$

gde su:

$f(X)$ - funkcija cilja,

$g_k(X) \le 0, \; k = 1,...,m$ - funkcije ograničenja,

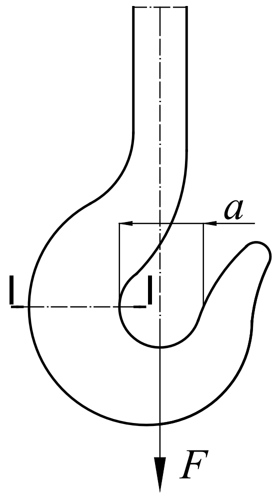
$l_i, u_i$ - granice donjeg, odnosno gornjeg ograničenja,

$m$ - broj funkcija ograničenja,

$n$ - broj projektnih varijabli,

$X = \{x_1,...,x_n\}^T$ - projektni vektor koga čine $n$ projektnih promenljivih (svaka projektna promenljiva je definisana svojom donjom i gornjom granicom).

Slika 1 prikazuje jednu standardnu dizaličnu kuku, prema [17], kao i kritični presek (*I - I*) na čijem se delu posmatra kritični poprečni presek.




*Slika 1: Dizalična kuka*

Matematička formulacija funkcije cilja prikazana je na sledeći način, (4):

$$f(X) = A(X) = A(x_1 \; ... \; x_n) \quad (4)$$

Vektor ulaznih parametara je:

$$\vec{x} = \left(Q, \; a, \; \sigma_{dop}\right) \quad (5)$$

gde su:

$Q$ - nosivost dizalične kuke,

$a$ - prečnik unutrašnjeg dela kuke (Slika 1), prema [17],

$\sigma_{dop}$ - kritični napon, [18].

U daljem tekstu će biti prikazane detaljno funkcije cilja i funkcije ograničenja.

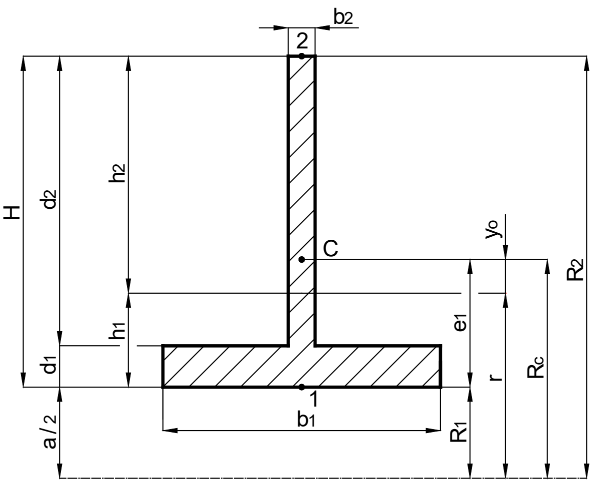
## 4. FUNKCIJE CILJA I FUNKCIJE OGRANIČENJA

### 4.1. Funkcija cilja za T poprečni presek

Funkcija cilja predstavlja površinu T poprečnog preseka dizalične kuke na najkritičnijem mestu konstrukcije kuke (Slika 2).

Površina poprečnog preseka, odnosno funkcija cilja, glasi:

$$A = A_T = b_1 \cdot d_1 + b_2 \cdot d_2 \quad (6)$$




*Slika 2: T poprečni presek*

Potrebne geometrijske veličine određuju se na sledeći način:

$$H = d_1 + d_2 \tag{7}$$

$$e_1 = \frac{b_1 \cdot d_1^2 + 2 \cdot b_2 \cdot d_1 \cdot d_2 + b_2 \cdot d_2^2}{2 \cdot A_T} \tag{8}$$

$$R_1 = \frac{a}{2} \tag{9}$$

$$R_2 = \frac{a}{2} + H \tag{10}$$

$$R_c = R_1 + e_1 \tag{11}$$

$$h_1 = r - R_1 \tag{12}$$

$$h_2 = R_2 - r \tag{13}$$

$$y_o = R_c - r \tag{14}$$

gde su:

$e_1$ - položaj težišta poprečnog preseka (Slika 2),

$R_1$ - poluprečnik unutrašnjeg vlakna (Slika 2),

$R_2$ - poluprečnik spoljašnjeg vlakna (Slika 2),

$R_c$ - poluprečnik težišne ose (Slika 2),

$r$ - poluprečnik neutralne ose (Slika 2),

$y_o$ - rastojanje između težišne i neutralne ose (Slika 2).

Ostale geometrijske veličine i varijable koje su predmet optimizacije su prikazane na Slici 2.

Poluprečnik neutralne ose se određuju na sledeći način, (15) i (16):

$$r = \frac{A_T}{\int_{A_T} \frac{dA}{\rho}} \tag{15}$$

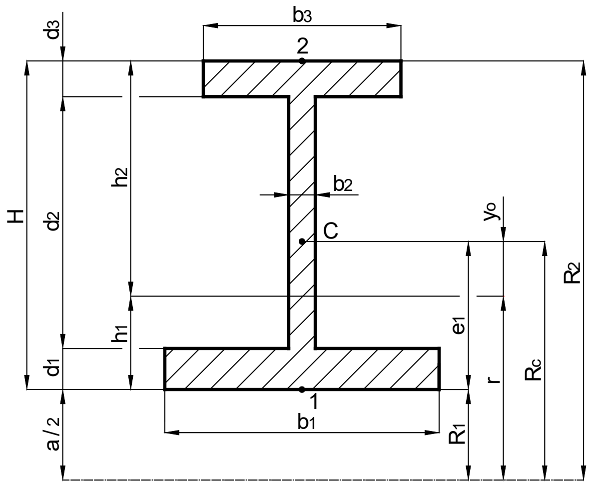
$$\int_{A_T} \frac{dA}{\rho} = b_1 \cdot \ln \frac{a + 2 \cdot d_1}{a} + b_2 \cdot \ln \frac{a + 2 \cdot H}{a + 2 \cdot d_1} \tag{16}$$

4.2. Funkcija cilja za I poprečni presek

Funkcija cilja predstavlja površinu I poprečnog preseka dizalične kuke na najkritičnijem mestu konstrukcije kuke (Slika 3).

Površina poprečnog preseka, odnosno funkcija cilja za ovaj poprečni presek, glasi:

$$A = A_I = b_1 \cdot d_1 + b_2 \cdot d_2 + b_3 \cdot d_3 \tag{17}$$




*Slika 3: I poprečni presek*

Potrebne geometrijske veličine određuju se na sledeći način:

$$H = d_1 + d_2 + d_3 \tag{18}$$

$$e_1 = \frac{b_1 \cdot d_1^2 + 2 \cdot b_2 \cdot d_1 \cdot d_2 + b_2 \cdot d_2^2}{2 \cdot A_I} + \frac{2 \cdot b_3 \cdot (d_1 + d_2) \cdot d_3 + b_3 \cdot d_3^2}{2 \cdot A_I} \tag{19}$$

Ostale veličine se određuju kao i u prethodnom slučaju, na osnovu izraza (9)÷(14).

Poluprečnik neutralne ose se određuju na sledeći način, (20) i (21):

$$r = \frac{A_I}{\int_{A_I} \frac{dA}{\rho}} \tag{20}$$

$$\int_{A_I} \frac{dA}{\rho} = b_1 \cdot \ln \frac{a + 2 \cdot d_1}{a} + b_2 \cdot \ln \frac{a + 2 \cdot (d_1 + d_2)}{a + 2 \cdot d_1} + b_3 \cdot \ln \frac{a + 2 \cdot H}{a + 2 \cdot (d_1 + d_2)} \tag{21}$$

Ostale geometrijske veličine i varijable koje su predmet optimizacije su prikazane na Slici 3.

4.3. Funkcije ograničenja

Proces optimizacije zasniva se na dozvoljenim naponima, prema Vinkler-Bakovoj teoriji, gde se kuka tretira kao krivolinijski štap, [18].

Matematička formulacija funkcija ograničenja, prema dopuštenim naponima, [18] u karakterističnim tačkama (Slika 2 i Slika 3) glasi:

$$g_1 = \sigma_1 = \frac{F}{A} + \frac{M_{\max}}{S_x} \cdot \frac{h_1}{R_1} \le \sigma_d \tag{22}$$

i

$$g_2 = |\sigma_2| = \frac{F}{A} - \frac{M_{\max}}{S_x} \cdot \frac{h_2}{R_2} \le \sigma_d \tag{23}$$

$$F = Q \cdot g \tag{24}$$

$$M_{\max} = F \cdot R_c \tag{25}$$

$$S_x = A \cdot y_o \tag{26}$$

gde su:

$F$ - sila usled težine terete (Slika 1),

$M_{\max}$ - maksimalni moment savijanja,

$S_x$ - statički moment površine poprečnog preseka.

Pored kriterijuma dozvoljenih napona, prisutna su i određena geometrijska ograničenja, što se tiče visine i širine profila:

$$g_3 = H \leq H_d \qquad (27)$$

$$g_4 = b_1, b_3 \leq H_d \qquad (28)$$

Takođe, u ovoj analizi je usvojeno da je debljina zidova profila minimum *0.5 cm*.

## 5. REZULTATI OPTIMIZACIJE

Optimizacija je sprovedena primenom algoritama optimizacije: CSS i TEO, korišćenjem kodova u izvornom obliku, prema [16], u MATLAB softverskom paketu.

Varijable optimizacije su $b_1$, $d_1$, $b_2$ i $d_2$, za T poprečni presek (Slika 2) i $b_1$, $d_1$, $b_2$, $d_2$, $b_3$ i $d_3$, za I poprečni presek (Slika 3).

Ulazni parametri za optimizaciju su: $Q=16\ t$, $a=14\ cm$ i $H_d=16\ cm$. Dozvoljeni napon uzima se u granicama od $\sigma_{dop}$=8÷10 $kN/cm^2$, za slučaj provere prema modelu kada nije uzet u obzir uticaj zakrivljenja kuke. Kako je sa uticajem zakrivljenja napon veći za 20÷30 %, u daljoj analizi će dozvoljeni napon biti uvećan za 20 % (usvojeno je $\sigma_{dop}=9.6\ kN/cm^2$). Površina poprečnog preseka standardne dizalične kuke na najkritičnijem mestu, u odnosu na koju se porede optimalni rezultati je: $A_s=140\ cm^2$, prema [17]. Za oba algoritma se uzima populacija od 200 agenata pretrage i 1000 iteracija.

U narednoj tabeli prikazani su rezultati optimizacije (optimalni geometrijski parametri poprečnog preseka, optimalna površina poprečnog preseka, karakteristike konvergencije i ušteda) prema gorenavedenim algoritmima za T poprečni presek (Tabela 1).

*Tabela 1: Rezultati optimizacije za T poprečni presek*

| Metod | CSS | TEO |
|---|---|---|
| $b_1$ (cm) | 16.0000 | 15.6821 |
| $d_1$ (cm) | 3.0122 | 2.9451 |
| $b_2$ (cm) | 2.6942 | 3.2233 |
| $d_2$ (cm) | 12.9715 | 12.7344 |
| Best=$A_T$ ($cm^2$) | **83.1431** | **87.2325** |
| Worst | 120.2749 | 137.9521 |
| Mean | 83.8904 | 90.7969 |
| Std | 3.2169 | 5.8564 |
| Vreme (s) | 176.98 | 7.34 |
| Ušteda (%) | 40.61 | 37.69 |

Takođe, posmatran je i slučaj kada su debljine $d_1$ i $b_2$ jednake (Tabela 2).

*Tabela 2: Rezultati optimizacije za T poprečni presek sa jednakim debljinama*

| Metod | CSS | TEO |
|---|---|---|
| $b_1$ (cm) | 15.9967 | 15.8871 |
| d (cm) | 2.8477 | 3.0267 |
| $d_2$ (cm) | 13.1418 | 12.6344 |
| Best=$A_T$ ($cm^2$) | **82.9766** | **86.3262** |
| Worst | 117.6697 | 130.2068 |
| Mean | 83.9506 | 89.1007 |
| Std | 2.0363 | 5.5078 |
| Vreme (s) | 171.04 | 7.78 |
| Ušteda (%) | 40.73 | 38.34 |

U narednoj tabeli prikazani su rezultati optimizacije (optimalni geometrijski parametri poprečnog preseka, optimalna površina poprečnog preseka, karakteristike konvergencije i ušteda) prema gorenavedenim algoritmima za I poprečni presek (Tabela 3).

*Tabela 3: Rezultati optimizacije za I poprečni presek*

| Metod | CSS | TEO |
|---|---|---|
| $b_1$ (cm) | 16.0000 | 15.4691 |
| $d_1$ (cm) | 2.3997 | 2.6180 |
| $b_2$ (cm) | 0.5000 | 0.5169 |
| $d_2$ (cm) | 12.4948 | 11.7841 |
| $b_3$ (cm) | 11.6725 | 9.5384 |
| $d_3$ (cm) | 1.0931 | 1.4124 |
| Best=$A_I$ ($cm^2$) | **57.4021** | **60.0605** |
| Worst | 127.4203 | 121.9845 |
| Mean | 58.8264 | 63.3623 |
| Std | 5.0985 | 8.1103 |
| Vreme (s) | 217.93 | 7.31 |
| Ušteda (%) | 59.00 | 57.10 |

Takođe, posmatran je i slučaj kada su debljine $d_1$, $b_2$ i $d_3$ jednake, kao i širine $b_1$ i $b_3$ (Tabela 4).

*Tabela 4: Rezultati optimizacije za I poprečni presek sa jednakim debljinama i širinama gornje i donje lamele profila*

| Metod | CSS | TEO |
|---|---|---|
| b (cm) | 15.9957 | 15.2752 |
| d (cm) | 1.8634 | 1.9975 |
| $d_2$ (cm) | 12.2403 | 11.9505 |
| Best=$A_I$ ($cm^2$) | **82.4212** | **84.8963** |
| Worst | 108.1320 | 109.1962 |
| Mean | 83.2402 | 86.2163 |
| Std | 2.6465 | 2.9343 |
| Vreme (s) | 216.19 | 7.27 |
| Ušteda (%) | 41.13 | 39.36 |

Na sledećim slikama prikazani su dijagrami konvergencije za pomenute metode optimizacije i oblike poprečnih preseka (Slika 4÷Slika 11).

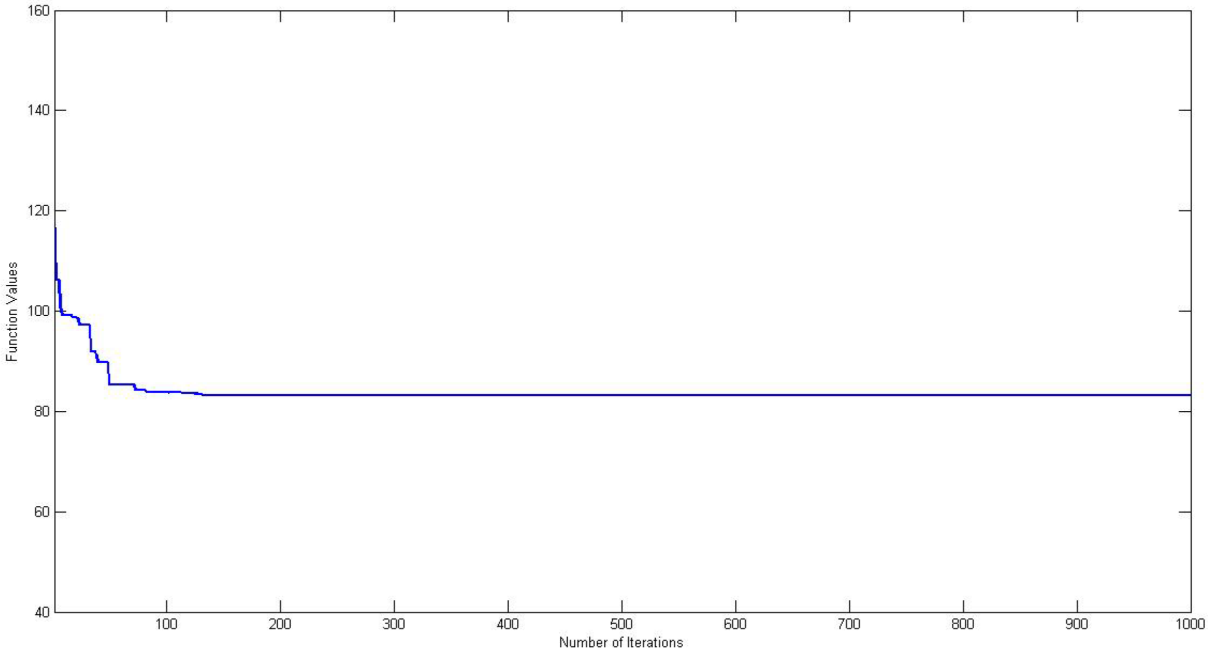
## 6. ZAKLJUČAK

U ovom radu su određeni optimalni geometrijski parametri T i I poprečnih preseka dizalične kuke na najkritičnijem mestu konstrukcije kuke, na jednom primeru dizalične kuke za nosivost od *16 t*, pri čemu je konstrukcija kuke tretirana kao krivolinijski štap. Kao funkcija cilja posmatrana je površina poprečnog preseka kuke, pri čemu su sva postavljena ograničenja zadovoljena. Optimizacija je sprovedena korišćenjem MATLAB softverskog paketa, primenom dva metaheuristička algoritma optimizacije inspirisana zakonima fizike: algoritam pretrage naelektrisanja sistema (CSS) i algoritam razmene toplote (TEO).

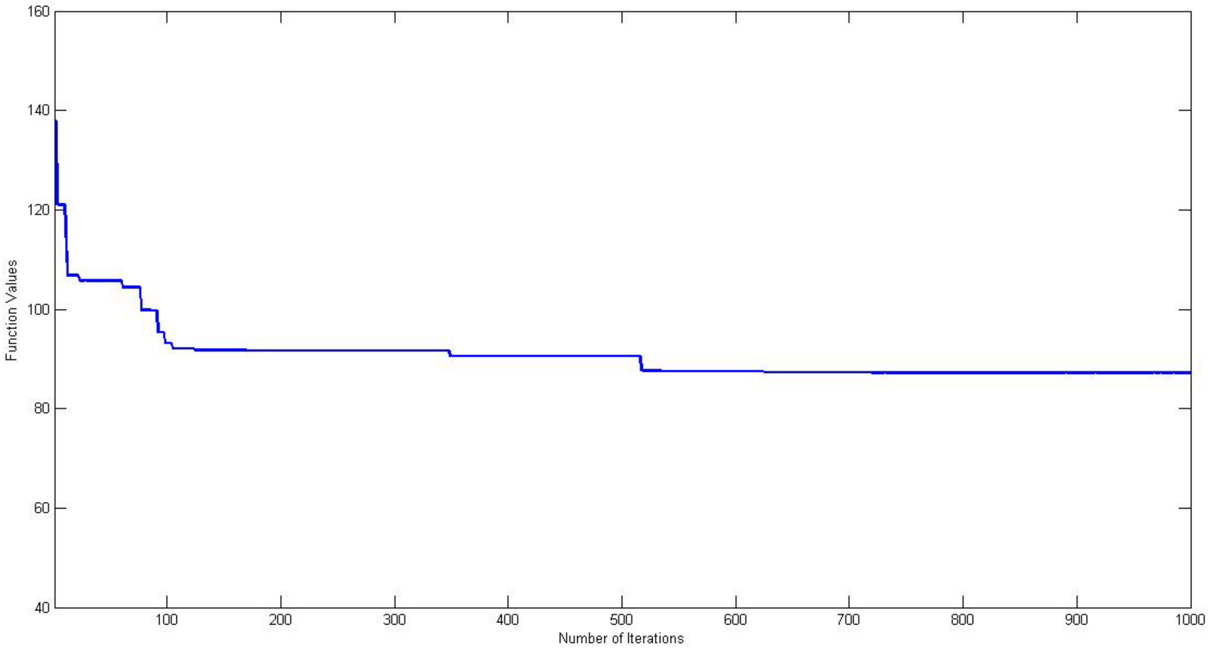
Postavljeni zadatak optimizacije, smanjenje površine poprečnog preseka dizalične kuke u njenom najkritičnijem preseku je uspešno realizovan, što se vidi na osnovu vrednosti ostvarenih ušteda, prikazanih u prethodnim tabelama (Tabela 1÷Tabela 4). Ovom prilikom je ostvarena ušteda od 40.73 % za T poprečni presek, dok je za I poprečni presek ostvarena ušteda čak od 59 %, za zadate uslove i ograničenja.

Može se primetiti, što se tiče T poprečnog preseka, na osnovu Tabele 1 i Tabele 2, da je nešto niže vrednosti optimalnih površina dao slučaj T poprečnog preseka sa jednakim debljinama, kod oba posmatrana algoritma optimizacije (Tabela 2). Primećuje se da su kod CSS algoritma vrednosti širine i visine profila jednake ili vrlo bliske graničnim vrednostima, dok su kod TEO algoritma ove vrednosti nešto ispod graničnih vrednosti. Ako se rezultati iz Tabele 1 uporede sa rezultatima iz [11], vidi se da su metaheuristički algoritmi FA, CS i SA postigli nešto veću uštedu u odnosu na CSS, dok je HS postigao gotovo indentičnu uštedu. TEO algoritam je ostvario najmanju uštedu u odnosu na ove pomenute algoritme optimizacije.

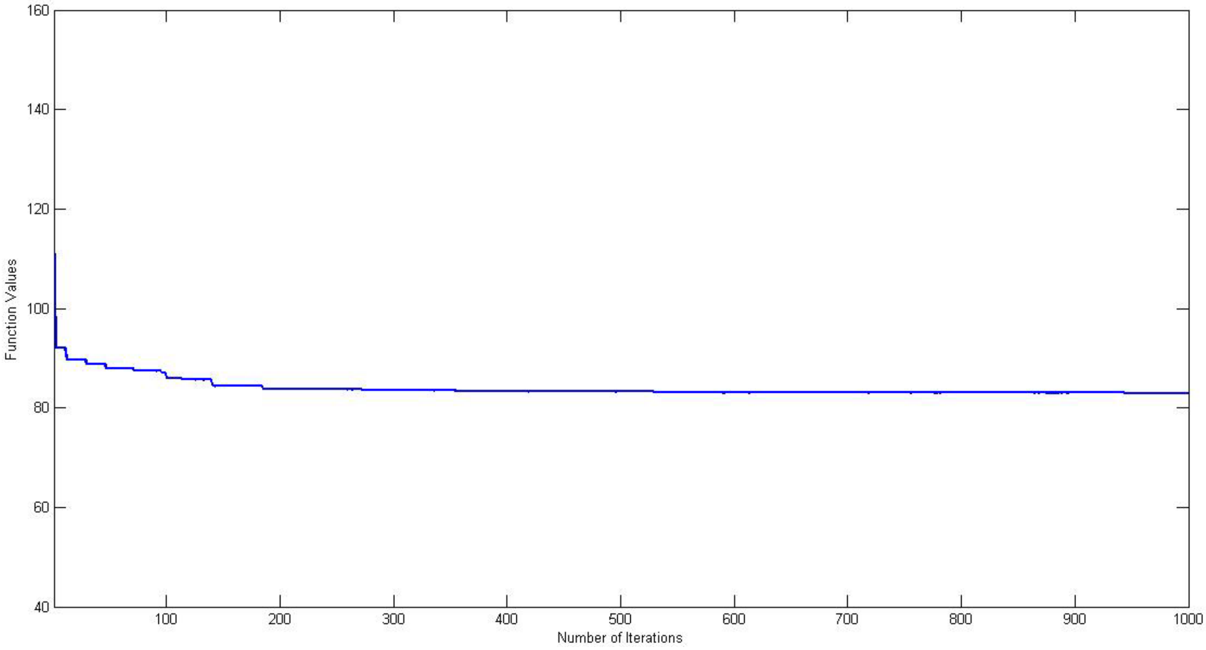
Kod I poprečnog preseka se primećuje da prva varijanta (Tabela 3) ostvaruje najmanju površinu poprečnog preseka u ovoj analizi, koja je dosta manja od varijante I poprečnog preseka koja je uslovljena jednakim debljinama profila i širinama gornje i donje lamele (Tabela 4), koja je dala najveću površinu (i najmanju uštedu) u ovom istraživanju. I ovde važi da CSS algoritam ostvaruje vrednosti širine i visine profila jednake ili vrlo bliske graničnim vrednostima, dok su kod TEO algoritma ove vrednosti nešto ispod graničnih vrednosti. I kod jedne i kod druge varijante bolje rezultate ostvaruje CSS algoritam.



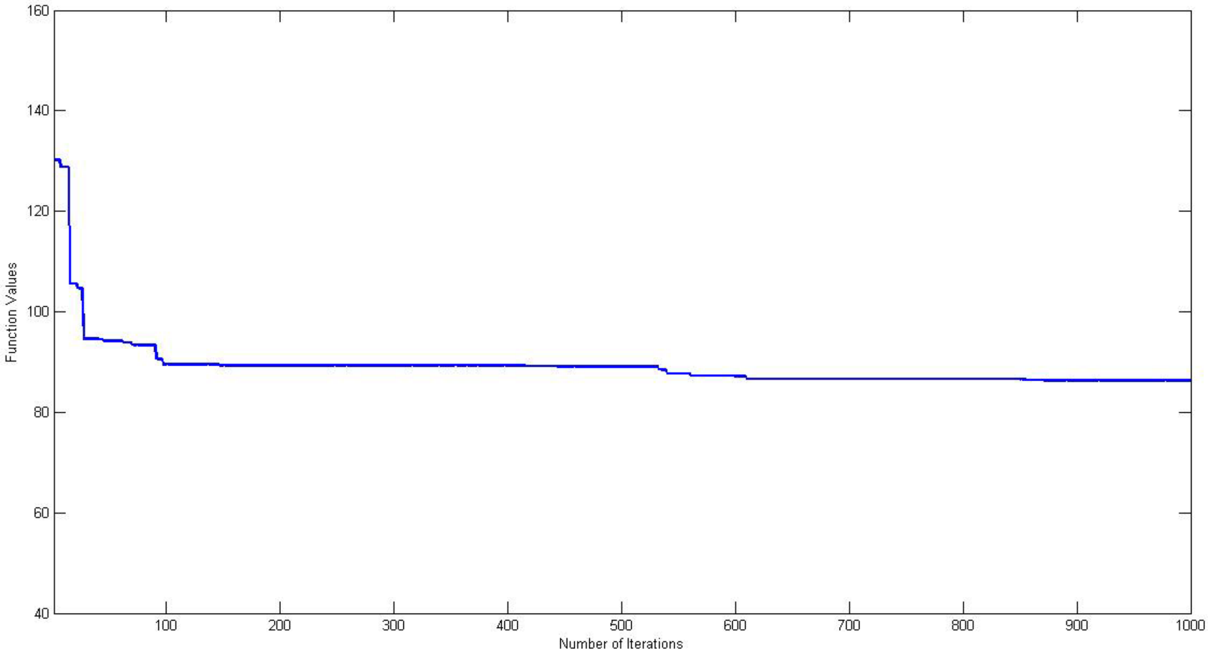

*Slika 4: Dijagram konvergencije za CSS za T poprečni presek*



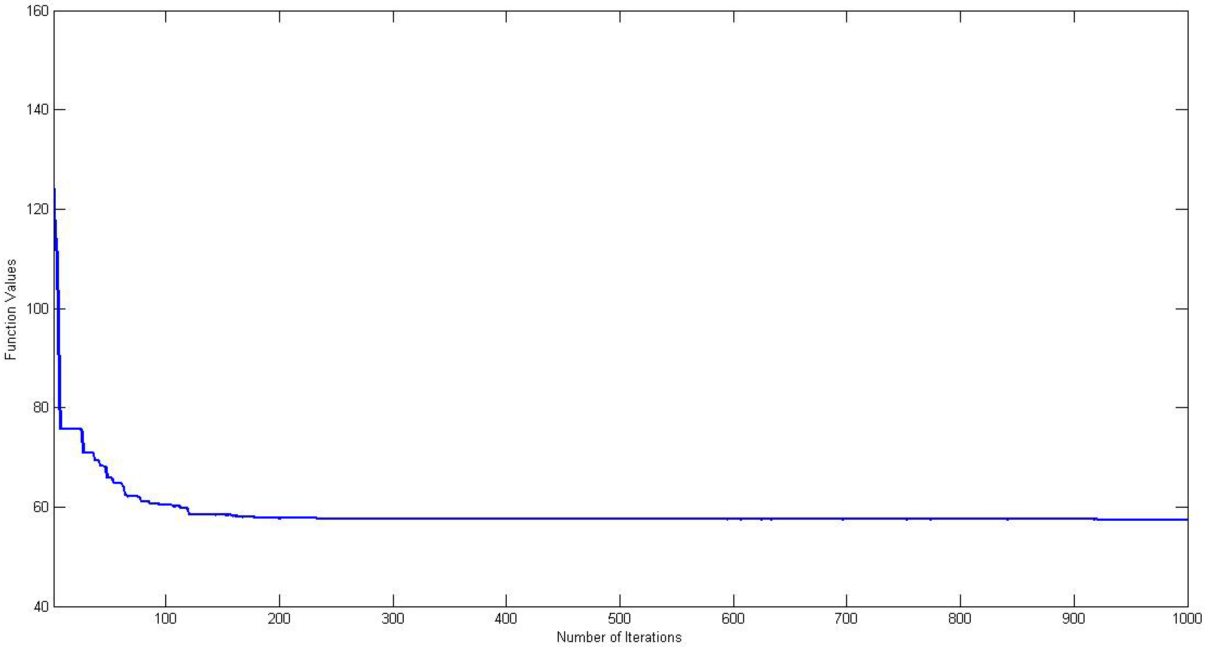

*Slika 5: Dijagram konvergencije za TEO za T poprečni presek*



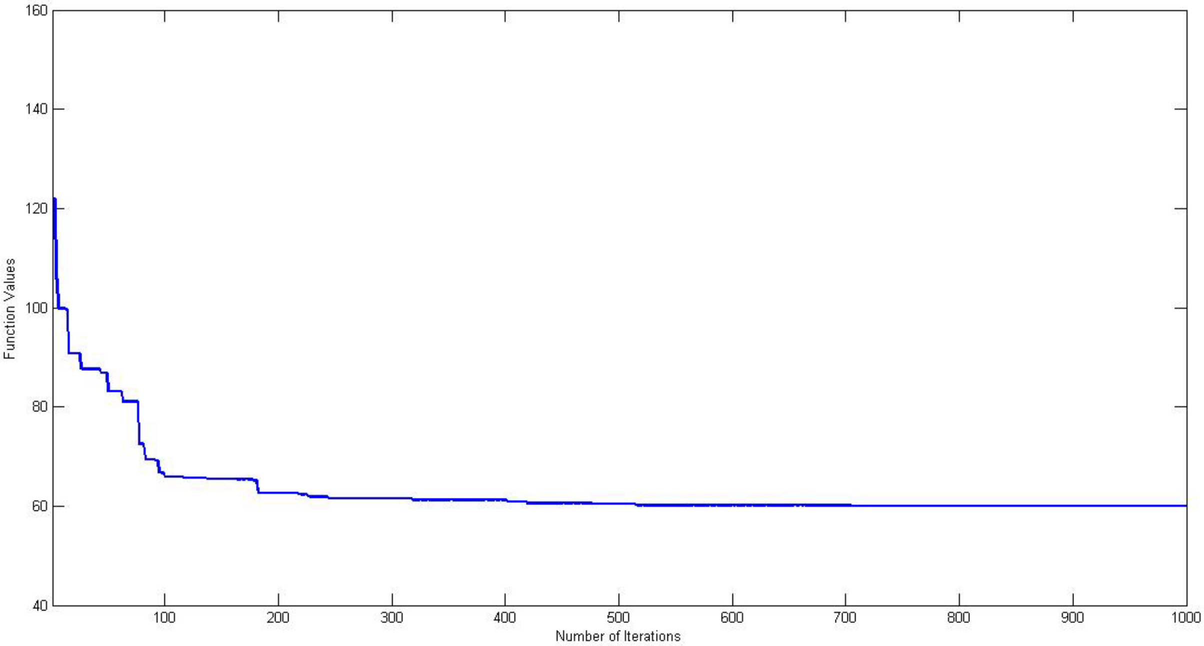

*Slika 6: Dijagram konvergencije za CSS za T poprečni presek sa jednakim debljinama*



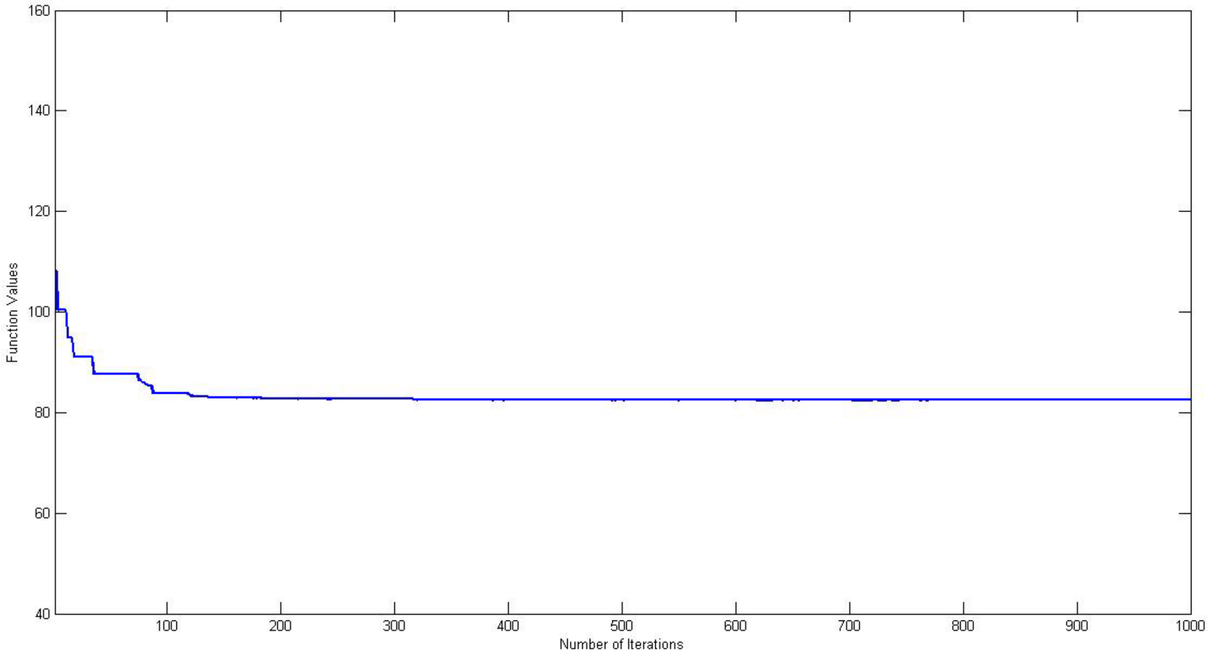

*Slika 7: Dijagram konvergencije za TEO za T poprečni presek sa jednakim debljinama*



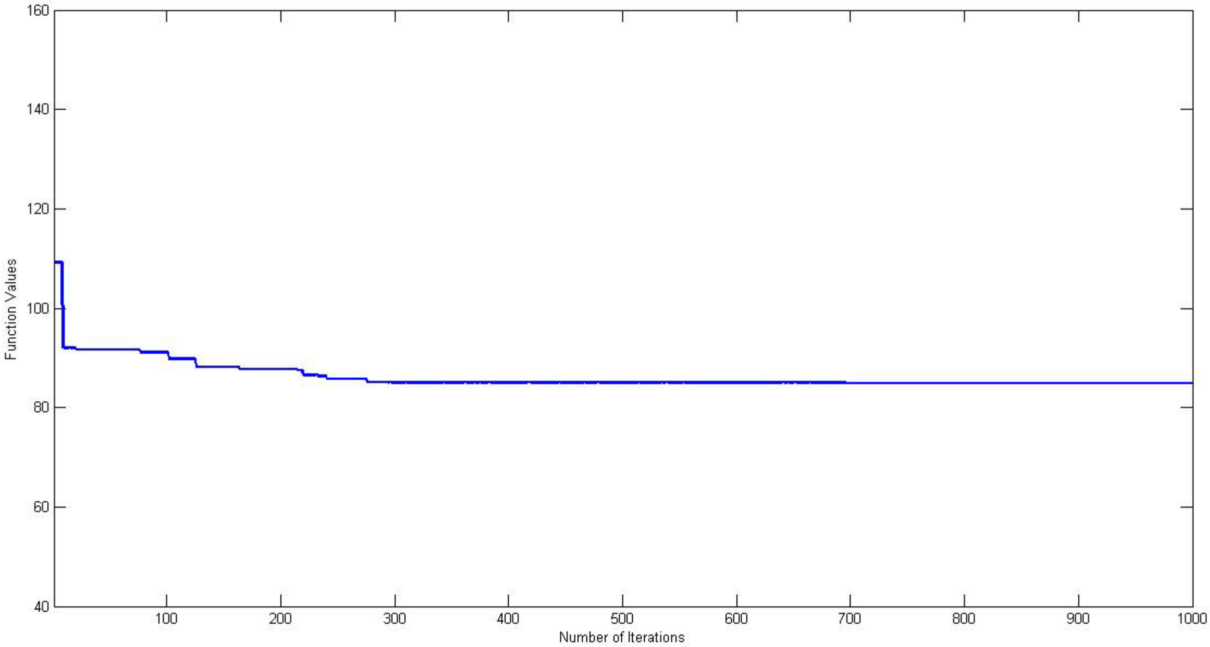

*Slika 8: Dijagram konvergencije za CSS za I poprečni presek*




*Slika 9: Dijagram konvergencije za TEO za I poprečni presek*




*Slika 10: Dijagram konvergencije za CSS za I poprečni presek sa jednakim debljinama i širinama gornje i donje lamele profila*




*Slika 11: Dijagram konvergencije za TEO za I poprečni presek sa jednakim debljinama i širinama gornje i donje lamele profila*

Što se tiče primenjenih algoritama optimizacije, najbolje rezultate ostvaruje CSS algoritam, u svim slučajevima, dok se do rešenja daleko brže dolazi primenom TEO algoritma, što se vidi na osnovu vremena potrebnog za rešavanje optimizacionog problema, prema zadatim početnim parametrima (Tabela 1÷Tabela 4). CSS algoritam bolje konvergira (Slika 4÷Slika 11), što se vidi i u tabelama, na osnovu vrednosti za standardnu devijaciju (Tabela 1÷Tabela 4). CSS algoritam je potrebno modifikovati u cilju skraćenja vremena za obavljanja postupka optimizacije, dok kod TEO algoritma je neophodno povećati tačnost.

Glavni zaključak na osnovu sprovedene analize i optimizacije je da posmatrani T i I poprečni preseci ostvaruju značajne uštede u materijalu u odnosu na standardno izvođenje dizalične kuke sa trapeznim poprečnim presekom. T poprečni presek u obe svoje varijante ostvaruje velike uštede, dok I poprečni presek u svojoj prvoj varijanti (6 varijabli) ostvaruje najbolju uštedu u prikazanom istraživanju (Tabela 3), dok je druga varijanta sa jednakim debljinama profila i uslovom o jednakim širinama lamela profila (3 varijable) dosta nepovoljna, jer se dobijaju daleko veće površine poprečnog preseka u odnosu na prvu varijantu, za zadate uslove i ograničenja.

Za dalja istraživanja je neophodno uključiti i druge geometrijske parametre strukture dizalične kuke. Takođe, potrebno je analizirati različite geometrijske preseke koji omogućuju svojom geometrijom da se pravilnim smanjenjem njene površine smanjuju i vrednosti napona, [13]. Tipove materijala i njihov pravilan izbor takođe trebaju da budu predmet rešavanje ovog inženjerskog problema.

Rezultate dobijene na ovaj način je potrebno verifikovati primenom MKE, kako bi se izveli određeni zaključci kod analize i optimizacije ovih tipova struktura.

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# Comparative Analysis and Optimization of T and I Cross Sections of Crane Hook using by Two Physics-Inspired Algorithms

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*This paper presents analysis and optimization of the geometric parameters of T and I cross-sections of crane hook, observed for the most critical location of its structure. The reduction of the cross-sectional area of crane hook was set as the goal in this study. The stresses at characteristic points of the most critical cross-section are taken as constraint functions, calculated according to Winkler-Bach theory, and some geometric conditions are set, too. Two metaheuristic algorithms based on the laws of physics, Charged System Search (CSS) algorithm and Thermal Exchange Optimization (TEO) algorithm, were selected for optimization methods, using by MATLAB software package. The goal of this research is to show that the proposed cross-sections give significant savings in comparison to standard crane hook, wherein the one standard capacity was observed. Both observed cross-sections were analyzed in two variants, and the comparison of their optimization results was performed to show which one achieves the best results. Also, the comparison of the applied optimization algorithms was performed.*

**Keywords: Crane hook, Optimization, Metaheuristic algorithms, MATLAB, Stresses**

## 1. INTRODUCTION

Crane hooks are highly responsible components for hanging and lifting of heavy load capacities. Manipulation with materials and with equipment using by these types of structures, is very present both at construction sites and production facilities, as well as in various types of industrial plants in the fields of maintenance and equipment installation.

Proper using of crane hooks can lead to efficiently manipulation with heavy loads, while improper using of them as well as improper selection can lead to the function cancellation, failures and accidents. The design of crane hook involves the determination of parameters such as the shape and area of the cross-section, type of material, the radius of curvature, etc. For this reason, it is necessary to pay attention to the proper choice of the shape and geometry of the cross-section of crane hook.

Because of its responsibilities and functions, problems of analysis and optimization of crane hook is the subject of research of many authors. The analysis of crane hook is performed by determining the stresses, and also the deformations, for certain geometric characteristics, usually, with some of software packages for FEM.

In the paper [1], FEM analysis of crane hook was performed using by ANSYS software package, with recommendations on how to prepare the model for this type of analysis. 3D model of hook was obtained using by Pro/Engineer software package. The value of the safety factor for this type of structure is determined. ANSYS was used in papers [2] and [3], too. In the paper [2], researchers performed analysis of one existing crane hook, comparing the results with analytical ones and with those obtained in previously published studies. In the paper [3], the authors analyze crane hooks of trapezoidal and rectangular cross-sections in order to obtain optimal dimensions that will give smaller cross-sectional areas, in comparision to existing standard solutions. The stresses and deformations of crane hook were observed in this analysis.

Comparison of different cross-sectional shapes is a very common topic in these type of studies. In the paper [4], comparison of various full cross-sectional shapes was performed using by ANSYS software package. Similar to the previous work, in the paper [5], comparison of cross-section of one standard hook, with modified shape of trapezoidal cross-section, circular cross-section and rectangular cross-section was performed, where the stress analysis was carried out using by ANSYS software package, while the 3D model was generated in CREO software package. CREO was applied in the paper [6], too, where the modification of the geometry of one crane hook, made according to ANSI standard, was done.

Comparison between T and I cross-sections of crane hook was done in the paper [7], where the analytical results were compared with those obtained by FEM analysis in ANSYS software package. In the paper [8], the authors performed analysis of Ramshorn hook using ANSYS software package, comparing circular cross-section with T and I cross-sections.

As can be seen, T and I cross-sections are increasingly used in analyzes of these types of structures. In the paper [9], comparative stress analysis was performed for the standard trapezoidal cross-section of the hook structure, as well as for T and I cross-sections. Modeling of these structures was performed using CATIA software package, and ANSYS Workbench was used for analysis. In [10], the optimization of T cross-section of crane hook was performed using by various numerical methods in the MATLAB and Ms EXCEL software packages.

Numerical optimization methods are increasingly being applied to engineering problems, especially metaheuristic optimization algorithms. In the paper [11], using by several metaheuristic algorithms, optimization of trapezoidal, elliptical and T cross-sections in MATLAB

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software package was carried out, wherein the standard specific capacities was observed.

In addition to the cross-sections of crane hook shown above, can be analyzed all potential shapes that can be considered. In addition to typical cross-sections, parabolic cross-section was considered in the paper [12]. In the paper [13], the authors indicate the paradox that occurs in the stresses in the cross-section of profile of hook, whereby the reduction in the area of cross-section at the appropriate places, or by changing the shape, may reduce the value of the stresses, with reducing its area.

Finally, considering all the above, the importance of optimization, as well as the results obtained in the presented studies, the main goal of this study is to obtain optimal geometric parameters for T and I cross-sections of crane hook, for one characteristic capacity at its most critical location, observing crane hook as a curved beam. Also, the results of the applied optimization methods will be compared, too.

## 2. APPLIED OPTIMIZATION ALGORITHMS

In this research optimization was performed using by two metaheuristic algorithms based on the laws of physics: Charged System Search (CSS) algorithm and Thermal Exchange Optimization (TEO) algorithm – using by MATLAB software package.

Charged System Search (CSS) algorithm was introduced in the paper [14], as an efficient population-based metaheuristic algorithm, inspired by physics. CSS utilizes the governing Coulomb laws from electrostatics and the Newtonian laws of mechanics. In this algorithm each agent is a charged particle with a predetermined radius. The charge of magnitude of particles is considered based on their quality. Each particle creates an electric field, which exerts a force on other electrically charged objects. The quantity of the resultant force is determined by using the electrostatics laws, and the quality of the movement is determined using Newtonian mechanics laws.

Thermal Exchange Optimization (TEO) algorithm is a relative new population-based metaheuristic algorithm, based on Newton's law of cooling, introduced in the paper [15]. Newton's law of cooling states that the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings. TEO considers each of its particles as a cooling or heating object, and by associating another agent as the environment, a heat transferring and thermal exchange happens between them. The new temperature of the object is considered as its next position in the search space, [15].

MATLAB codes for both metaheuristic algorithms of optimization used in this paper, in their original form, without modifications, are taken according to [16].

## 3. MATHEMATICAL FORMULATION OF OPTIMIZATION PROBLEM

The task of optimization for this engineering problem is to determine the optimal geometrical parameters for T and I cross-sections of structure of crane hook at its most critical location, which will minimize its cross-sectional area.

The optimization problem is defined in following way:

minimization of the objective function:

$$f(X) \quad (1)$$

subject to the constrain functions:

$$g_k(X) \le 0,\ k = 1,...,m \quad (2)$$

where it is fulfilled:

$$l_i \le X_i \le u_i,\ i = 1,...,n \quad (3)$$

where:

$f(X)$ - the objective function,

$g_k(X) \le 0,\ k = 1,...,m$ - the constrain functions,

$l_i, u_i$ - the lower and upper constraint limit,

$m$ - the number of constrains,

$n$ - the number of design variables,

$X = \{x_1,...,x_n\}^T$ - a project vector of $n$ project variables (each project variable is defined by its lower and upper limit).

Fig. 1 shows one standard crane hook, according to [17], as well as the most critical location (*I - I*) on which part is the critical cross-section observed.

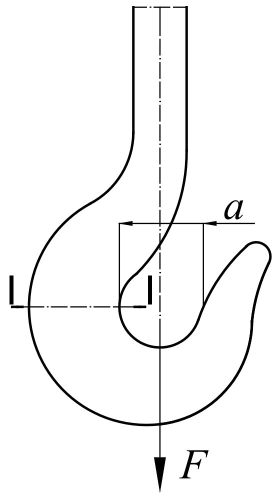


*Figure 1: Crane hook*

The mathematical formulation of the objective function is shown as follows, (4):

$$f(X) = A(X) = A(x_1 \ ...\ x_n) \quad (4)$$

The vector of input parameters is:

$$\vec{x} = (Q,\ a,\ \sigma_{dop}) \quad (5)$$

where:

$Q$ - load capacity,

$a$ - inner diameter (Fig. 1), according to [17],

$\sigma_{dop}$ - critical stress, [18].

Below will be present the objective function and the constraint functions.

## 4. OBJECTIVE FUNCTIONS AND CONSTRAINT FUNCTIONS

### 4.1. Objective function for T cross-section

The objective function is represented by the area of T cross-section of crane hook at the most critical location (Fig. 2).

The cross-sectional area, the objective function, is:

$$A = A_T = b_1 \cdot d_1 + b_2 \cdot d_2 \quad (6)$$

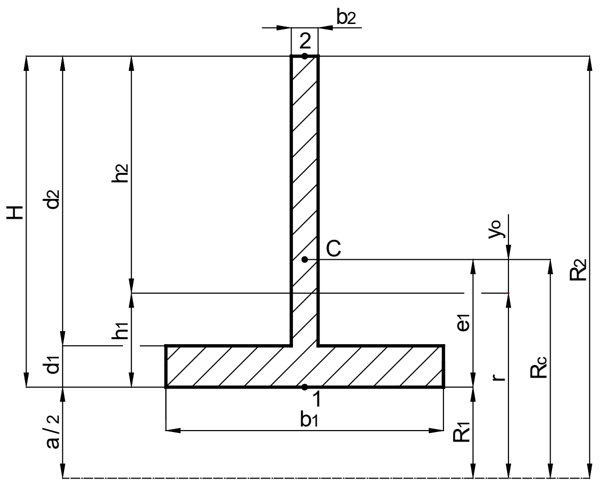


*Figure 2: T cross-section*

The required geometric parameters are determined as follows:

$$H = d_1 + d_2 \tag{7}$$

$$e_1 = \frac{b_1 \cdot d_1^2 + 2 \cdot b_2 \cdot d_1 \cdot d_2 + b_2 \cdot d_2^2}{2 \cdot A_T} \tag{8}$$

$$R_1 = \frac{a}{2} \tag{9}$$

$$R_2 = \frac{a}{2} + H \tag{10}$$

$$R_c = R_1 + e_1 \tag{11}$$

$$h_1 = r - R_1 \tag{12}$$

$$h_2 = R_2 - r \tag{13}$$

$$y_o = R_c - r \tag{14}$$

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 centroidal axis (Fig. 2),

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

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

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

The radius of neutral axis is defined in following way, (15) and (16):

$$r = \frac{A_T}{\int_{A_T} \frac{dA}{\rho}} \tag{15}$$

$$\int_{A_T} \frac{dA}{\rho} = b_1 \cdot \ln \frac{a + 2 \cdot d_1}{a} + b_2 \cdot \ln \frac{a + 2 \cdot H}{a + 2 \cdot d_1} \tag{16}$$

4.2. Objective function for I cross-section

The objective function is represented by the area of I cross-section of crane hook at the most critical location (Fig. 3).

The cross-sectional area, the objective function, is:

$$A = A_I = b_1 \cdot d_1 + b_2 \cdot d_2 + b_3 \cdot d_3 \tag{17}$$

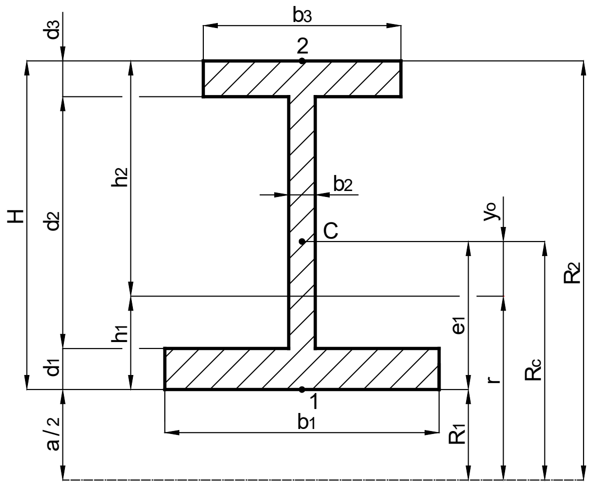


*Figure 3: I cross-section*

The required geometric parameters are determined as follows:

$$H = d_1 + d_2 + d_3 \tag{18}$$

$$e_1 = \frac{b_1 \cdot d_1^2 + 2 \cdot b_2 \cdot d_1 \cdot d_2 + b_2 \cdot d_2^2}{2 \cdot A_I} + \frac{2 \cdot b_3 \cdot (d_1 + d_2) \cdot d_3 + b_3 \cdot d_3^2}{2 \cdot A_I} \tag{19}$$

Other parameters are determined as in the previous case, based on the expressions (9)÷(14).

The radius of neutral axis is defined in following way, (20) and (21):

$$r = \frac{A_I}{\int_{A_I} \frac{dA}{\rho}} \tag{20}$$

$$\int_{A_I} \frac{dA}{\rho} = b_1 \cdot \ln \frac{a + 2 \cdot d_1}{a} + b_2 \cdot \ln \frac{a + 2 \cdot (d_1 + d_2)}{a + 2 \cdot d_1} + b_3 \cdot \ln \frac{a + 2 \cdot H}{a + 2 \cdot (d_1 + d_2)} \tag{21}$$

Other geometrical parameters and variables that are the subject of optimization, are shown in Fig. 3.

4.3. Constraint functions

The optimization process is based on allowable stresses, according to Winkler-Bach theory, where crane hook is treated as a curved beam, [18].

The mathematical formulation of the constrain functions, according to the allowed stresses, [18] in characteristic points (Fig. 2 and Fig. 3) are:

$$g_1 = \sigma_1 = \frac{F}{A} + \frac{M_{\max}}{S_x} \cdot \frac{h_1}{R_1} \le \sigma_d \tag{22}$$

and

$$g_2 = |\sigma_2| = \frac{F}{A} - \frac{M_{\max}}{S_x} \cdot \frac{h_2}{R_2} \le \sigma_d \tag{23}$$

$$F = Q \cdot g \tag{24}$$

$$M_{\max} = F \cdot R_c \tag{25}$$

$$S_x = A \cdot y_o \tag{26}$$

where:

$F$ - axial force (Fig. 1),

$M_{\max}$ - maximum bending moment,

$S_x$ - static moment of area.

In addition to the stress criteria, there are also certain geometric constraints, which are related to the height and width of the profile:

$$g_3 = H \leq H_d \tag{27}$$

$$g_4 = b_1, b_3 \leq H_d \tag{28}$$

Also, in this analysis is adopted that minimum value of thickness of the profile is *0.5 cm*.

## 5. RESULTS OF OPTIMIZATION

Optimization is carried out using by optimization algorithms: CSS and TEO, with codes in its standard form, according to [16], in MATLAB software package.

The optimization variables are $b_1$, $d_1$, $b_2$ and $d_2$, for T cross-section (Fig. 2) and $b_1$, $d_1$, $b_2$, $d_2$, $b_3$ and $d_3$, for I cross-section (Fig. 3).

Input parameters for optimization are: $Q=16$ *t*, $a=14$ *cm* and $H_d=16$ *cm*. The permissible stress is taken within the interval $\sigma_{dop}=8\div10$ $kN/cm^2$, for the case of stress check in a model where the hook curvature is not considered. Since the curvature of the hook makes the equivalent stress increase for 20÷30 %, the permissible stress will also be increased by 20 % in further analysis (adopted value is $\sigma_{dop}$=9.6 $kN/cm^2$). The cross-sectional area of standard crane hook at the most critical location, in comparison to which the optimal results are compared is: $A_s=140$ $cm^2$, prema [17]. For both algorithms population size is 200 search agents and 1000 number of iterations.

The following table shows the results of optimization (optimal cross-sectional geometric parameters and area, convergence characteristics and savings) according to the above algorithms for T cross-section (Table 1).

*Table 1: Results of optimization for T cross-section*

| Method | CSS | TEO |
|---|---|---|
| $b_1$ (cm) | 16.0000 | 15.6821 |
| $d_1$ (cm) | 3.0122 | 2.9451 |
| $b_2$ (cm) | 2.6942 | 3.2233 |
| $d_2$ (cm) | 12.9715 | 12.7344 |
| Best=$A_T$ ($cm^2$) | **83.1431** | **87.2325** |
| Worst | 120.2749 | 137.9521 |
| Mean | 83.8904 | 90.7969 |
| Std | 3.2169 | 5.8564 |
| Time (s) | 176.98 | 7.34 |
| Saving (%) | 40.61 | 37.69 |

*Table 2: Results of optimization for T cross-section for same thickness*

| Method | CSS | TEO |
|---|---|---|
| $b_1$ (cm) | 15.9967 | 15.8871 |
| d (cm) | 2.8477 | 3.0267 |
| $d_2$ (cm) | 13.1418 | 12.6344 |
| Best=$A_T$ ($cm^2$) | **82.9766** | **86.3262** |
| Worst | 117.6697 | 130.2068 |
| Mean | 83.9506 | 89.1007 |
| Std | 2.0363 | 5.5078 |
| Time (s) | 171.04 | 7.78 |
| Saving (%) | 40.73 | 38.34 |

Also, the case where the thickness $d_1$ and $b_2$ are equal (Table 2) are observed.

The following table shows the results of optimization (optimal cross-sectional geometric parameters and area, convergence characteristics and savings) according to the above algorithms for I cross-section (Table 3).

*Table 3: Results of optimization for I cross-section*

| Method | CSS | TEO |
|---|---|---|
| $b_1$ (cm) | 16.0000 | 15.4691 |
| $d_1$ (cm) | 2.3997 | 2.6180 |
| $b_2$ (cm) | 0.5000 | 0.5169 |
| $d_2$ (cm) | 12.4948 | 11.7841 |
| $b_3$ (cm) | 11.6725 | 9.5384 |
| $d_3$ (cm) | 1.0931 | 1.4124 |
| Best=$A_I$ ($cm^2$) | **57.4021** | **60.0605** |
| Worst | 127.4203 | 121.9845 |
| Mean | 58.8264 | 63.3623 |
| Std | 5.0985 | 8.1103 |
| Time (s) | 217.93 | 7.31 |
| Saving (%) | 59.00 | 57.10 |

Also, the case where the thickness $d_1$, $b_2$ and $d_3$ are equal, and the width of profile flange $b_1$ and $b_3$ are equal (Table 4).

*Table 4: Results of optimization for I cross-section for same thickness and same width of profile flange*

| Method | CSS | TEO |
|---|---|---|
| b (cm) | 15.9957 | 15.2752 |
| d (cm) | 1.8634 | 1.9975 |
| $d_2$ (cm) | 12.2403 | 11.9505 |
| Best=$A_I$ ($cm^2$) | **82.4212** | **84.8963** |
| Worst | 108.1320 | 109.1962 |
| Mean | 83.2402 | 86.2163 |
| Std | 2.6465 | 2.9343 |
| Time (s) | 216.19 | 7.27 |
| Saving (%) | 41.13 | 39.36 |

The following figures show the convergence diagrams for the mentioned methods of optimization and cross-sectional shapes (Fig. 4÷Fig. 11).

## 6. CONCLUSION

In this paper the optimal geometrical parameters of T and I cross-sections of crane hook at the most critical location of the hook structure are determinated, in the case of crane hook for a load capacity of *16 t*, where the hook structure is treated as a curved beam. The cross-sectional area of hook was observed as the objective function, where all set constraints are satisfied. The optimization was carried out using MATLAB software package, using by two metaheuristic optimization algorithms inspired by the laws of physics: Charged System Search (CSS) algorithm and Thermal Exchange Optimization (TEO) algorithm.

The optimization task, the reduction of the cross-sectional area of crane hook for its most critical cross-section was successfully realized, as can be seen from the values of savings shown in the previous tables (Table 1÷Table 4). In this case, a saving of 40.73% was achieved for T cross-section, while for I cross-section, savings of as much as 59% were achieved, for the given conditions and constraints.

It can be observed, for T cross-section, based on Table 1 and Table 2, that a slightly lower value of optimal areas gave the variant of T cross-section with equal thickness of profile, for both observed optimization algorithms (Table 2). It is noted that for CSS algorithm the values of width and height of the profile are equal or very close to the limit values, while for TEO algorithm these values are slightly below to the limit values. If the results of Table 1 are compared with those of [11], it can be seen that the metaheuristic algorithms FA, CS and SA achieved slightly higher savings in comparision to CSS, while HS achieved almost identical savings. TEO algorithm has made the least savings over these aforementioned optimization algorithms.

For I cross-section, it can be observed that the first variant (Table 3) gave the smallest cross-sectional area in this analysis, which is much smaller than the variant of I cross-section with same thickness and same width of profile flange (Table 4), which is gave the largest area (and the least savings) in this research. In this case, too, CSS algorithm realizes the value of width and height profile of equal or very close to the limit values, while for TEO algorithm, these values are slightly below the limit values. For both variants, CSS algorithm performs better results.

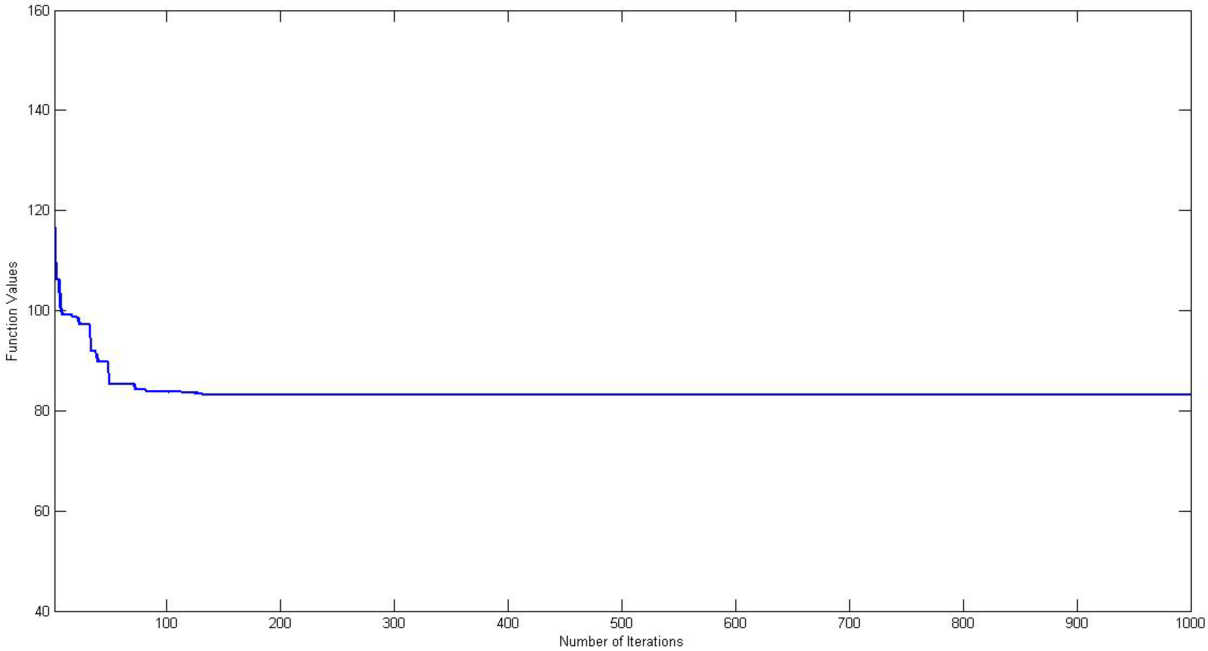


*Figure 4: Convergence diagram of CSS for T cross-section*

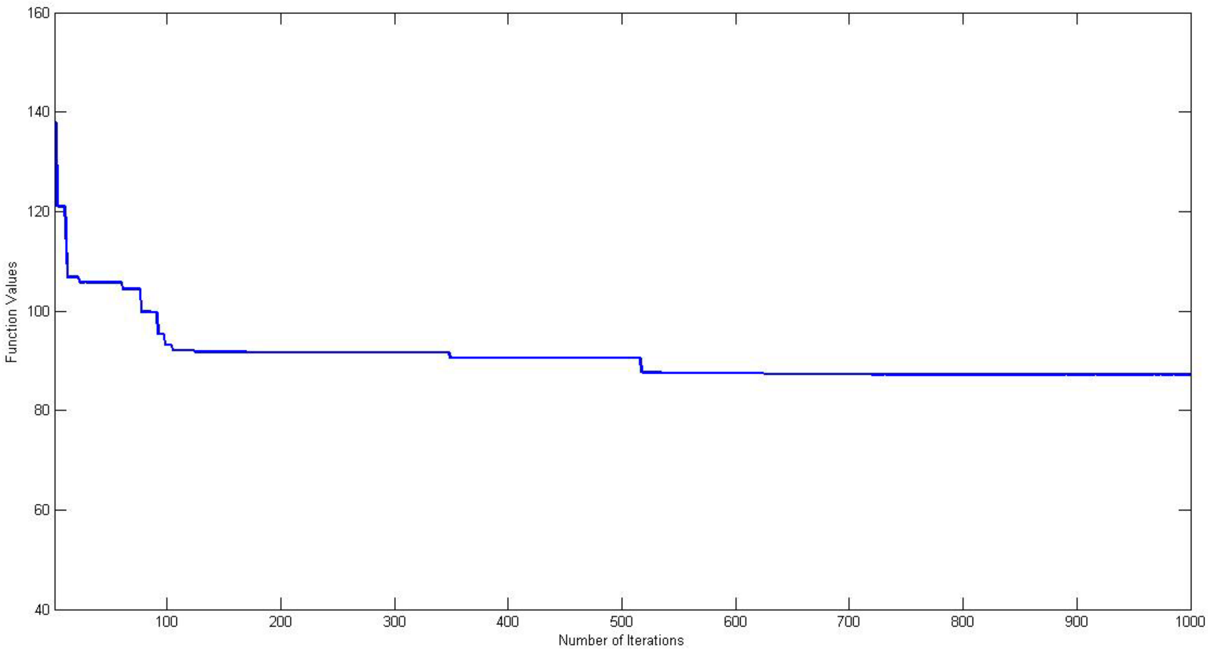


*Figure 5: Convergence diagram of TEO for T cross-section*

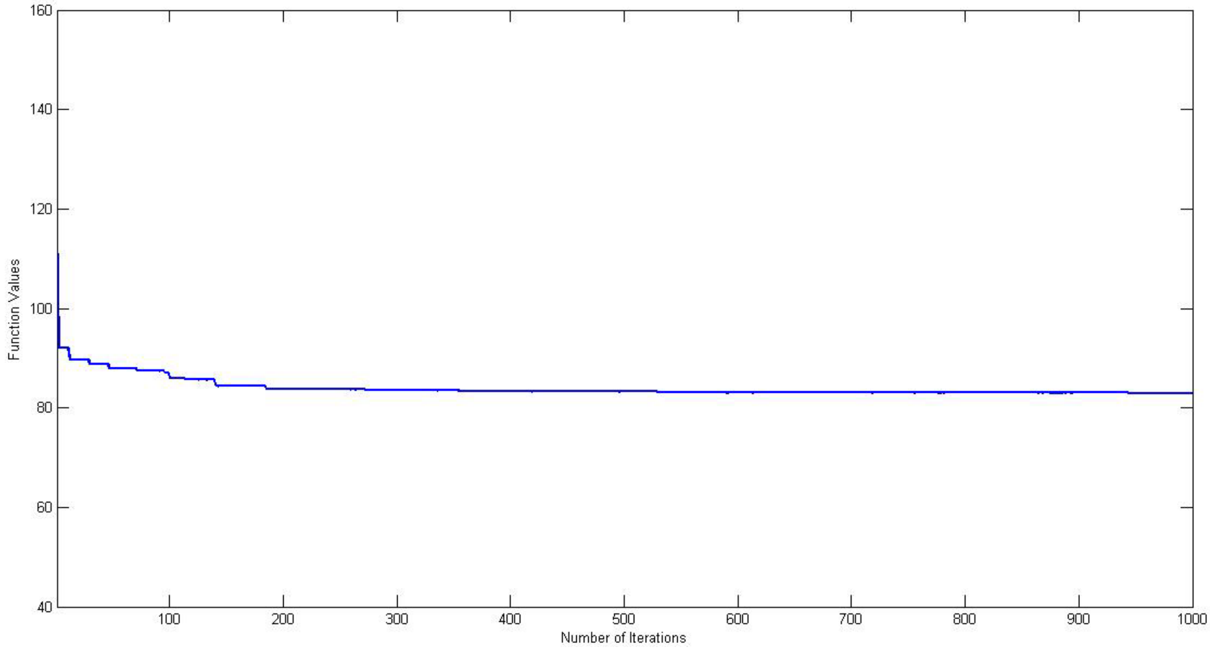


*Figure 6: Convergence diagram of CSS for T cross-section for same thickness*

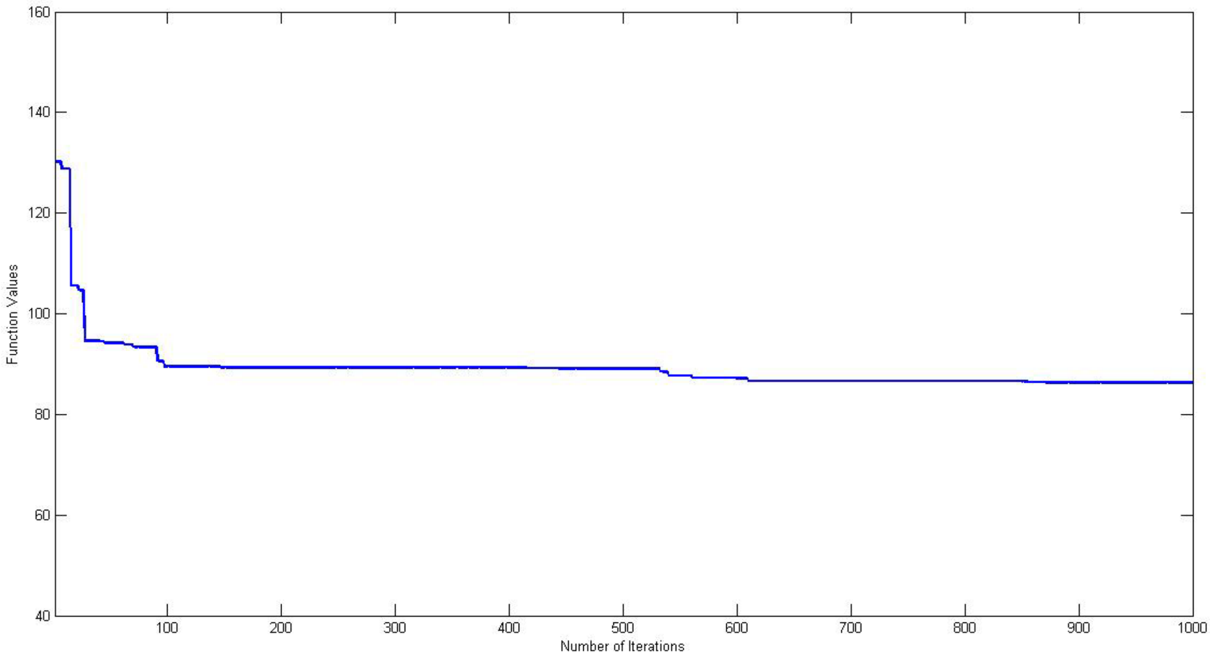


*Figure 7: Convergence diagram of TEO for T cross-section for same thickness*

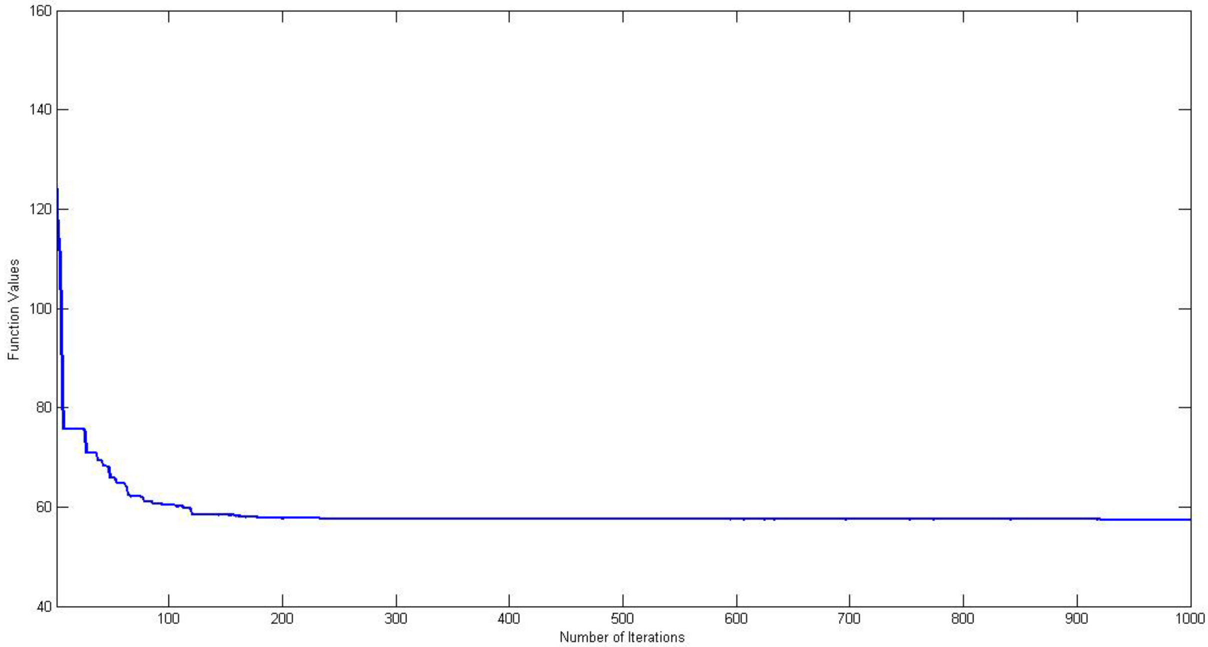


*Figure 8: Convergence diagram of CSS for I cross-section*

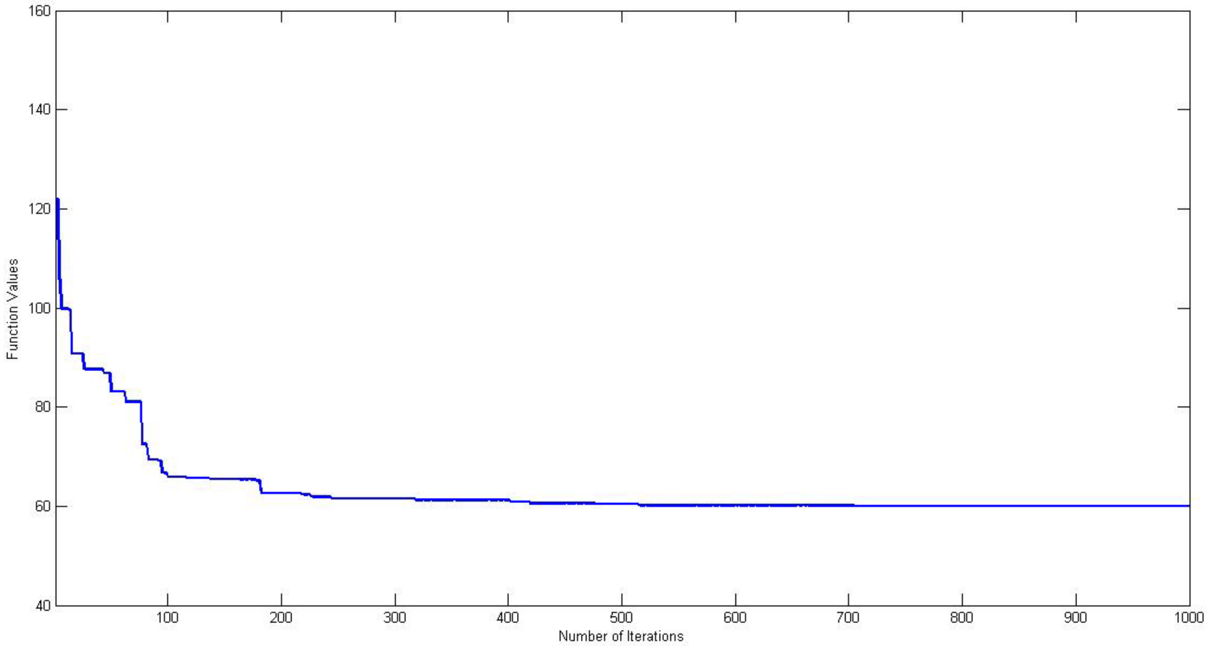


*Figure 9: Convergence diagram of TEO for I cross-section*

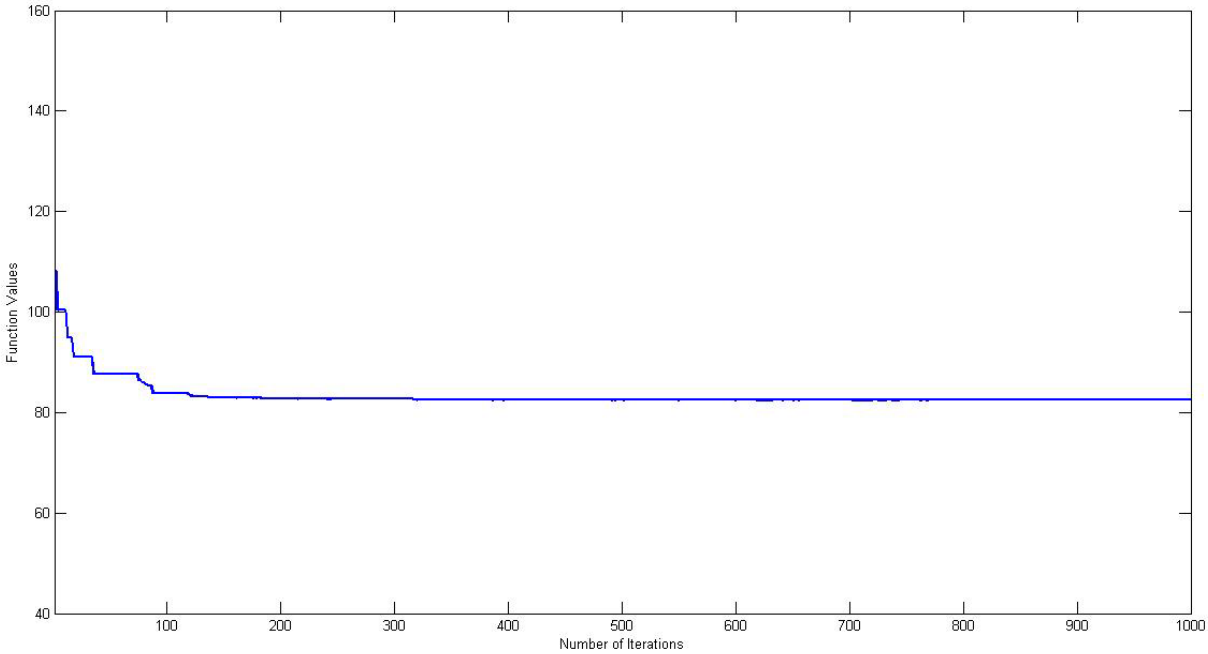


*Figure 10: Convergence diagram of CSS for I cross-section for same thickness and same width of profile flange*

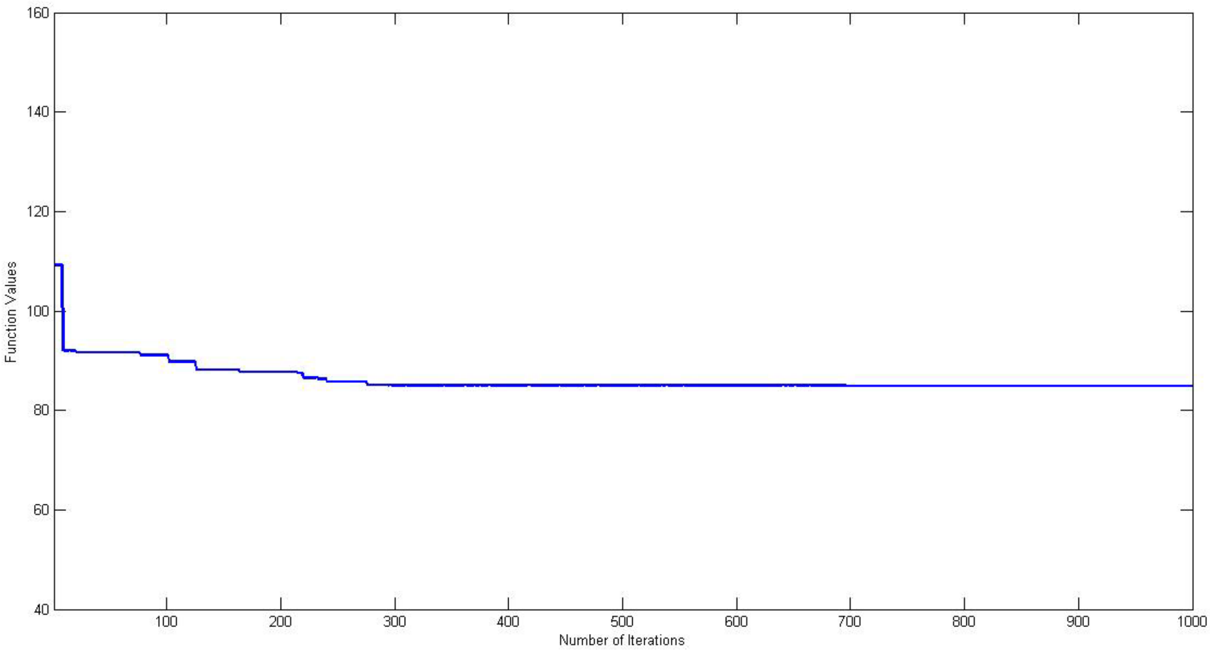


*Figure 11: Convergence diagram of TEO for I cross-section for same thickness and same width of profile flange*

With regard to applied optimization algorithms, the best results are achieved by CSS algorithm, in all cases, while the solutions are achieved much faster by application of TEO algorithm, which is evident from the values of time required to solve the optimization problem, according to the given initial parameters (Table 1÷Table 4). CSS algorithm has better convergence (Figure 4÷Figure 11), which is also seen in the tables, based on the values for standard deviation (Table 1÷Table 4). CSS algorithm needs to be modified to shorten the time to perform the optimization process, while TEO algorithm needs to be modified to increase accuracy.

The main conclusion based on conducted analysis and optimization is that the observed T and I cross-sections have significant material savings in comparision to the standard solution of crane hook with trapezoidal cross-section.

T cross-section in both its variants making significant savings, while I cross-section in its first versiant (6 variables) achieved the best savings in this research (Table 3), while the second variant with same thickness and same width of profile flange (3 variables) is rather unfavorable, because it gives far larger cross-sectional area in comparision to the first variant, for given conditions and constrains.

For further research it is necessary to include other geometric parameters of the crane hook structure. Also, it is necessary to analyze the different geometrical cross-sections which enable its proper geometry to decrease its value of area and reduce stresses, [13]. Types of materials and their correct choice should also be subject to solve this engineering problem.

The results obtained in this way is necessary to verify by FEM, in order to perform certain conclusions for analysis and optimization of these types of structures.

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