Goran Pavlović
Research Associate
University of Niš
Faculty of Electronic Engineering

Mile Savković
Full Professor
University of Kragujevac
Faculty of Mechanical and Civil Engineering in Kraljevo

Nebojša Zdravković
Associate Professor
University of Kragujevac
Faculty of Mechanical and Civil Engineering in Kraljevo

Goran Marković
Associate Professor
University of Kragujevac
Faculty of Mechanical and Civil Engineering in Kraljevo

Marko Todorović
Assistant
University of Kragujevac
Faculty of Mechanical and Civil Engineering in Kraljevo

Low-weight design of a monosymmetric box girder of a double girder bridge crane with two trolleys

The paper presents the analysis and the optimization (weight reduction) of the two-trolley double-girder bridge crane box-girder by the Lightning Attachment Procedure Optimizer (LAPO) algorithm. The single-objective function workflow uses the geometric properties of the box-like cross-section plates and additional design elements as variables. This multi-criteria optimization uses the maximum stresses in cross-section characteristic points, plate local stability, the stability of longitudinal stiffeners, global girder stability, structure's oscillation dumping time and maximum deflections as the constraint functions. The existing bridge design saw a significant weight reduction of 17.89% for material S355 and 16.90% for material S275. Finally, the features of the chosen algorithm and optimum solution change flow for ten simulations are presented for the best solution achieved for both materials.

Keywords: *Steel Girder, Bridge Crane, Optimal Design, Metaheuristic, Lightning Attachment Procedure Optimizer.*

1. INTRODUCTION

The weight reduction of the bridge crane's main girder can be achieved with many procedures. For example, the paper [1] showed the redesign of an existing double girder bridge crane by reducing the thicknesses and dimensions of the plates of the main girder, where the analysis was conducted by the finite element method (FEM) in ANSYS software. Herein, a weight saving of 8.39% was achieved compared to the existing solution. Furthermore, the weighted decision matrix was applied in [2] to optimize geometric parameters of the double girder bridge crane main girder based on three concepts – minimum weight, minimum deflection and minimum stress. This analysis was done by FEM based on the stress and deformation states of the structure. As a result, the optimum design was produced and verified by testing. The research [3] presents a nonlinear FEM analysis of the double girder bridge crane main girders for defined spans and payloads to optimize the girders. The code for optimization was developed using interpolation ratios and correction factors to obtain optimized results (with or without considering industrial constraints).

In [4], a three-dimensional parametric finite element model is established. The limit load-bearing ability of the main girder of a true crane is predicted using the arc-length algorithm and nonlinear stabilization algorithm, respectively. Also, the software platform of optimal design for double-trolley overhead travelling cranes is developed based upon the lightweight design conception.

The analysis and optimization of the main bridge crane girders have many conditions and limitations. Numerous publications show that many metaheuristic algorithms (original and advanced forms, hybridized algorithms) are applied to achieve the lightweight design of these engineering structures, considering it a multi-criteria problem. The paper [5] presents the Multi-Specular Reflection Algorithm (M-SRA) application for the lightweight and green design of the double girder bridge crane main girder. The research [6] shows the application of the discrete Imperialist Competitive Algorithm (ICA) optimization in conjunction with the reliability-based design optimization (RBDO) procedure on the optimization problem of the box-like cross-section of double girder bridge crane girder. The appliance of the RBDO method upon actual bridge crane structure obtains the best compromise between economy and safety. The Modified Particle Swarm Optimization (MPSO) method was used to optimize the geometric parameters of the bridge crane main girder in [7]. It has been confirmed that this method achieves better results and has better features than the PSO algorithm. The optimization problem of the box-like cross-section of the double girder bridge crane girder with the rail in the middle of the girder was studied by Simulated Annealing (SA) and Harmony Search (HS) algorithms in [8]. Bio-inspired optimization algorithms were successfully applied to the single-beam bridge crane girder in [9], where significant savings were made in considered examples of cranes in exploitation.

Previous publications [5-9] show that metaheuristic algorithms gain more application in engineering practice, particularly in mechanical and civil engineering design [10,11].

This research aims to reduce the weight of the main girder of one existing double girder bridge crane with two trolleys [12]. All necessary conditions were

Correspondence to: Goran V. Pavlović, research associate
University of Niš, Faculty of Electronic Engineering,
Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: goran.pavlovic@elfak.ni.ac.rs

considered within the analysis [13,14]. The research used the Lightning Attachment Procedure Optimizer (LAPO) algorithm, which can be utilized equally successful in solving single-objective [15] and multi-objective [16] optimization problems. The algorithm was used without any modifications. This algorithm was successfully utilized in various engineering problems [17-19].

2. OPTIMIZATION PROBLEM

The optimization problem in this research is the weight decrease of the mono-symmetric box-like cross-section girder of the double girder bridge crane (Fig. 1). The crane has two trolleys as described in [12], and the working platform on the main girder. Since the paper [12] was used as a basis for this research, the loading scheme and the calculus method for the forces acting upon the main girder were inherited. Also, the same crane was analyzed here.

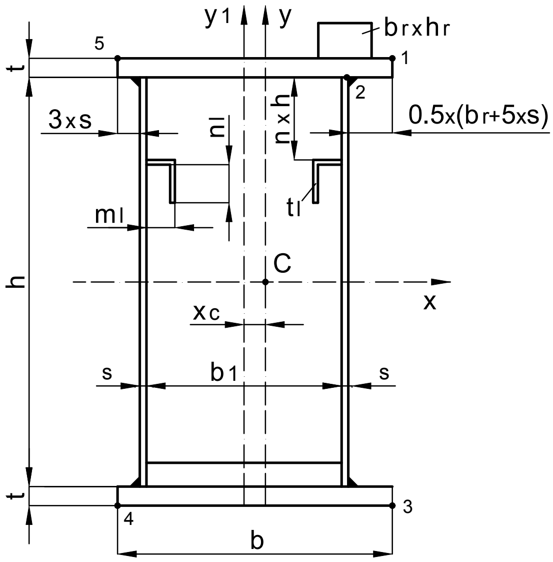

Figure 1. The cross-sectional area of a box girder

The girder consists of the plates that form a box-like cross-section (Fig. 1) and additional elements such as diaphragms and longitudinal stiffeners (Fig. 2). The diaphragms' dimensions depend on the plates' dimensions, while the longitudinal L-shape stiffeners are cold-formed to the required dimension.

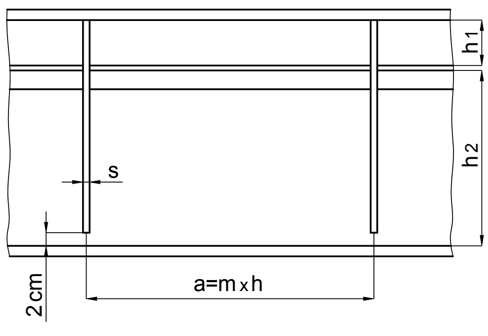

Figure 2. Inner elements of a box girder

The objective function is the main girder's weight, consisting of plates, diaphragms, and longitudinal stiffeners (Fig. 1 and Fig. 2).

It can be written as reads (1):

$$f_{ob} = M = M_p + M_d + M_L \tag{1}$$

where:
M - the total weight of the girder,
M_p - the weight of plates,
M_d - the weight of diaphragms, and
M_L - the weight of longitudinal stiffeners.

The weights of girder components in relation to project variables are shown in section 2.1.

2.1 Optimization variables

This optimization problem includes the following design variables (Fig. 1 and Fig. 2): $x_1=t$, $x_2=s$, $x_3=b_1$, $x_4=h$, $x_5=m$, $x_6=n$, $x_7=m_l$, $x_8=n_l$, $x_9=t_l$

where:
t - the flange thickness,
s - the web thickness,
b_1 - the inner width of the box profile,
h - the web height,
m - a relation that defines the distance between the diaphragms,
n - a relation that defines the position of the longitudinal stiffener,
m_l - the longitudinal stiffener width,
n_l - the longitudinal stiffener height, and
t_l - the longitudinal stiffener thickness.

The weights of girder components can be now written as:

$$M_p = \rho \cdot A \cdot L \tag{2}$$

$$M_d = \rho \cdot n_d \cdot A_d \cdot s \tag{3}$$

$$M_L = 2 \cdot \rho \cdot A_L \cdot L \tag{4}$$

where:
ρ - the density of the girder material,
A - the area of plates,
L - a bridge crane span,
n_d - the number of diaphragms,
A_d - the area of the diaphragm, and
A_L - the area of the longitudinal stiffener (Fig. 1):

$$A = 2 \cdot \left(b \cdot t + h \cdot s \right) \tag{5}$$

$$A_d = b_1 \cdot \left(h - 2 \right) \tag{6}$$

$$A_L = t_l \cdot \left(m_l + n_l \right) \tag{7}$$

where b is the flange width (Fig. 1):

$$b = b_1 + 4 \cdot s + \left(7 \cdot s + b_r \right) / 2 \tag{8}$$

where b_r is the rail width (Fig. 1).

Variables are the values that should be defined during the optimization process.

2.2 Constraint functions

Many criteria and conditions have to be satisfied within this complex optimization problem.

Considered constraint functions were the stress values in characteristic points of the girder, stability of the plates and longitudinal stiffeners, global stability of the girder, oscillation dumping time and vertical and horizontal deflections.

Within the strength criterion, it is necessary to satisfy stress values in particular points of a box-like cross-section (Fig. 1), where the maximum load in a critical point on the girder is obtained according to [12].

At points (Fig. 1) i = 1, 3, 4, and 5, the maximum stress σ_i is determined according to (9):

$$\sigma_i = \frac{M_{V,\max}}{W_{i,x}} + \frac{M_{H,\max}}{W_{i,y}} \leq \sigma_{dop} = \frac{R_{e,1}}{\upsilon_1} \tag{9}$$

where:
$M_{V,max}$ and $M_{H,max}$ - maximum bending moments in the vertical and horizontal plane, respectively, [12],
$W_{i,x}$ and $W_{i,y}$ - section moduli for point i about x and y direction, respectively,
σ_{dop} - the permissible stress,
v_1 - load case 1 factored load coefficient, according to [14], and
$R_{e,1}$ - the minimum yield stress of the plate material, according to [14].

At point 2, due to wheel pressure on the rail above the vertical plate, a complex stress state occurs (σ_2):

$$\sigma_2 = \sqrt{\sigma_{2z}^2 + \sigma_y^2 - \sigma_{2z}\sigma_y + 3\tau_2^2} \leq \sigma_{dop} \tag{10}$$

$$\sigma_{2z} = \frac{M_{V,\max}}{W_{2,x}} + \frac{M_{H,\max}}{W_{2,y}} \leq \sigma_{dop} \tag{11}$$

$$\sigma_y = \frac{\gamma \cdot F_1}{s \cdot z_1} \leq \sigma_{dop} \tag{12}$$

$$\tau_2 = \tau_{12} + \tau_{22} \leq \tau_{dop} = \frac{\sigma_{dop}}{\sqrt{3}} \tag{13}$$

$$\tau_{12} = \frac{F_t \cdot S_{2x}}{I_x \cdot 2 \cdot s} \tag{14}$$

$$\tau_{22} = \frac{M_{tA}}{A^* \cdot 2 \cdot s} \tag{15}$$

where:
σ_{2z} - the normal (bending) stress at the point 2,
σ_y - the normal stress at the point 2, due to the pressure of the wheel on the rail,
τ_{dop} - the permissible tangential stress,
τ_2 - the total tangential stress at the point 2,
τ_{12} and τ_{22} - components of the tangential stress due to shear and torsion, respectively,
γ - the coefficient, according to [13],
F_1 - the acting force from the trolley wheel 1 in the vertical plane, according to [12],
F_t - the shear force, according to [13],
M_{ta} - the moment of torsion, according to [13],
I_x - the moment of inertia about the x-axis,
A^* - the enclosed area of the mean periphery of the thin-walled closed section, and
S_{2x} - the static moment of area about x-axis for the point 2.

The plates' local stability check comprises the stability check for the upper compressed flange, the vertical plate above which the rail is placed and the other vertical plate. The diaphragms are placed along the girder, while the vertical plates are braced with one row of longitudinal stiffeners (Fig. 1 and Fig. 2).

The local stability check of the flange plate with length a (Fig. 2) and width b_1 is to be done according to [13]:

$$\sigma_p = \nu_1 \cdot \sigma_{p,\max} \leq \min\left(\sigma_{dop,p}, R_{e,1}\right) \tag{16}$$

where:
σ_p - the design value of the compressive stress at the top flange,
$\sigma_{p,max}$ - the maximum stress at the top flange, and
$\sigma_{dop,p}$ - the critical stress for the local stability of the top flange.

The girder is not symmetric in the x-direction, so the sign changes of inertial force make different load cases (both section sides, left and right, can be compressed or extended). Therefore, two load cases were considered here. The critical case was taken for the stress calculation (16).

Concerning the stability of vertical plates, the checks were conducted for the plate with the length a and the width h_1 (section 1) and the plate with the length a and the width h_2 (section 2), Fig.1 and Fig. 2.

The local stability check for the vertical plate with rail above was done according to [13]:

$$\nu_1 \cdot \left(\frac{\sigma_r}{\sigma_{kr1}} + \frac{\sigma_y}{\sigma_{Mkr1}}\right) + \left(\frac{\nu_1 \cdot \tau_r}{\tau_{kr1}}\right)^2 \leq 0,9 \tag{17}$$

$$\nu_1 \cdot \left(\frac{\sigma_r}{\sigma_{kr2}} + \frac{0,4 \cdot \sigma_y}{\sigma_{Mkr2}}\right) + \left(\frac{\nu_1 \cdot \tau_r}{\tau_{kr2}}\right)^2 \leq 1 \tag{18}$$

where:
σ_r - the maximum normal stress,
τ_r - the maximum tangential stress,
σ_{kr1},-σ_{Mkr1} and τ_{kr1} - critical stresses for area 1, and
σ_{kr2}, σ_{Mkr2} and τ_{kr2} - critical stresses for area 2.

The local stability check for the other vertical plate was done according to [13]:

$$\sigma_{w1} = \nu_1 \cdot \sigma_{w1,\max} \leq \min\left(\sigma_{dop,w1}, R_{e,1}\right) \tag{19}$$

$$\sigma_{w2} = \nu_1 \cdot \sigma_{w2,\max} \leq \min\left(\sigma_{dop,w2}, R_{e,1}\right) \tag{20}$$

where:
σ_{w1} - the design value of the compressive stress for area 1,
$\sigma_{w1,max}$ - the maximum stress for area 1,

$\sigma_{dop,w1}$ - the critical stress for area 1,
σ_{w2} - the design value of the compressive stress for area 2,
$\sigma_{w2,max}$ - the maximum stress for area 2, and
$\sigma_{dop,w2}$ - the critical stress for area 2.

The stability of longitudinal stiffeners was conducted according to [13]:

$$\nu_1 \cdot \sigma_l \leq \chi_l \cdot R_{e,2} \quad (21)$$

$$m_l / t_l \leq 0,665 \cdot \sqrt{K_\sigma \cdot E / R_{e,2}} \quad (22)$$

where:
σ_l - the maximum stress at the longitudinal stiffener place, according to [13],
χ_l - a reduction factor, according to [13],
$R_{e,2}$ - the minimum yield stress of the longitudinal stiffeners, according to [14],
K_σ - the coefficient, according to [13], and
E - the elastic modulus of the material.

The global stability of the girder is checked according to [14], i.e.:

$$(b_1 + s)/t \leq 1,33 \cdot \sqrt{E / R_{e,1}} \quad (23)$$

$$(b_r + 6s)/2t \leq 0,454 \cdot \sqrt{E / R_{e,1}} \quad (24)$$

$$(h + t)/(b_1 + s) \leq 10 \quad (25)$$

$$\sigma_b = \nu_1 \cdot \sigma_{b,\max} \leq \min(\sigma_{dop,b}, R_{e,1}) \quad (26)$$

where:
σ_b - the design value of the compressive stress for global stability,
$\sigma_{b,max}$ - the maximum stress for global stability, and
$\sigma_{dop,b}$ - the critical stress for global stability.

Oscillation dumping time (T) is determined on a simplified model, where it is assumed that both trolleys are placed in the middle of the bridge crane, [13]:

$$T = \frac{\pi \cdot \ln(20)}{\gamma_d} \cdot \sqrt{\frac{m_1 \cdot L^3}{12 \cdot E \cdot I_x}} \leq T_{dop} \quad (27)$$

where:
γ_d - the logarithmic decrement, [13], and
T_{dop} - the permissible relaxation time of girder oscillation, [13].

The reduced weight (m_1) is determined as:

$$m_1 = Q + m_t + 1,25 \cdot m_r \quad (28)$$

where:
Q - a bridge crane payload (a carrying capacity),
m_t - the weight of the trolley, and
m_r - reduced weight of the girder (increased 25%):

$$m_r = \frac{17}{35} \rho \left(A + 2A_L + \frac{n_d \cdot A_d \cdot s}{L} + A_s \right) L \quad (29)$$

where A_s is the rail area.

Vertical and horizontal deflection checks are done for the middle point of the crane span:

$$f_V \leq f_{V,d} \quad (30)$$

$$f_H \leq f_{H,d} \quad (31)$$

where:
f_V and f_H - the total deflections in the vertical and horizontal plane, respectively, and
$f_{V,d}$ and $f_{H,d}$ - the permissible deflections in the vertical and horizontal plane, respectively.

The values of permissible deflections in both planes are given in [12].

The calculation of the total deflection values is conducted on principle described in [12], with static load values determined for the middle point of the girder.

3. OPTIMIZATION RESULTS

A double girder bridge crane with a carrying capacity of 2 x 25 t and a span of 22,5 m was used as an example for the optimization procedure [12]. All necessary design data for the mentioned bridge crane were taken based on [12], and all other necessary parameters for the optimization process were taken according to [13], based on the Classification class and other operating conditions of the bridge crane.

The material of the main girder plates is steel S355, and the structural elements S235. In this analysis, it is observed how the optimal weight of the whole structure of the main girder changes based on the change of the main girder plates material from S355 to S275.

R_e=35,5 kN/cm^2, for S355, and
R_e=27,5 kN/cm^2, for S355.

The optimization process was performed by using MATLAB code for the Lightning Attachment Procedure Optimizer (LAPO) algorithm.

The objective function is defined by (1).

Constraints are defined by (9)-(13), (16)-(27), (30), and (31).

Bound values of variables are:
$0,6 \leq x_1 \leq 3$, $0,5 \leq x_2 \leq 2$, $25 \leq x_3 \leq 50$,
$60 \leq x_4 \leq 150$, $1 \leq x_5 \leq 2$, $3 \leq x_6 \leq 10$, $2,5 \leq x_7 \leq 8$,
$0,3 \leq x_8 \leq 1$, $1/5 \leq x_9 \leq 1/3$.

The control parameters of the LAPO algorithm are:
N_{pop} = 100 - population size, and
Max_it = 1000 - maximum number of iterations.

The optimization procedure was performed by performing ten simulations.

Fig. 3 and Figs. 4 show the optimal weights of the main girder of the observed bridge crane example (for ten simulations) for materials S355 and S275, respectively.

Table 1 presents the optimization results (optimal values of variables and characteristics of optimization process:
best - the best value,
worst – the worst value,
mean – the mean value, and
Std – standard deviation) for both types of material.

The results were taken as the best solutions achieved during the simulations.

Table 2 presents the rounded values of optimal geometric parameters, weights of the main girder, and savings in material for both types of material.

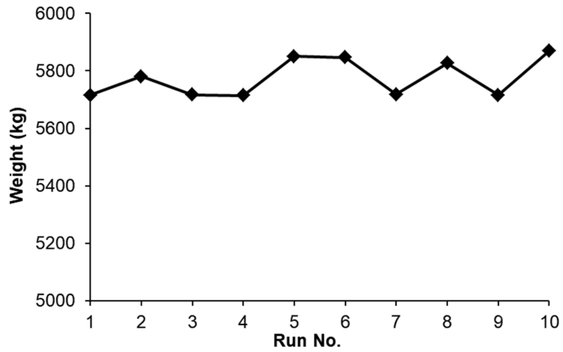

Figure 3. The low-weight design for S355

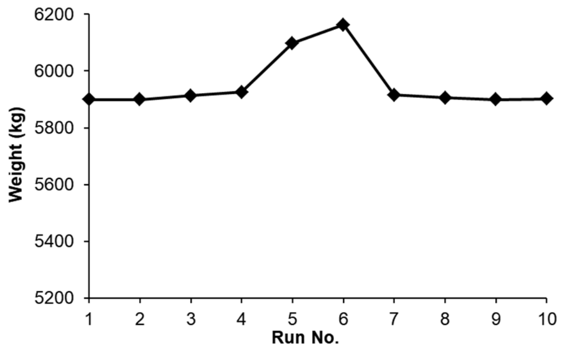

Figure 4. The low-weight design for S275

The following graphs show the convergence diagrams for materials S355 and S275 (best solutions achieved during the simulations), respectively (Fig. 5 and Fig. 6).

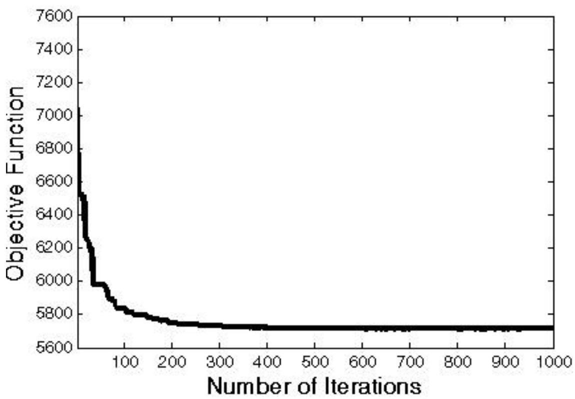

Figure 5. Convergence diagram for S355

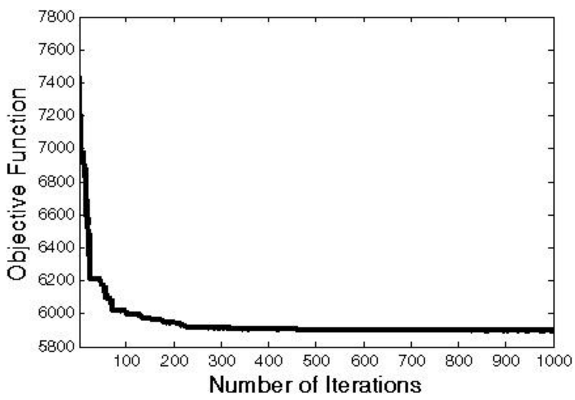

Figure 6. Convergence diagram for S275

4. CONCLUSION

This research deals with the low-weight design of the main girder of a double girder bridge crane with two trolleys. The Lightning Attachment Procedure Optimizer (LAPO) algorithm was used for the optimization procedure. The objective function is the weight of the main girder. The criteria of stresses, local buckling of the girder plates (webs and top flange), local buckling of the longitudinal stiffeners, global buckling of the main girder, period of oscillation, and deflections in the vertical and horizontal planes were applied as the constraint functions.

The results obtained in this research (savings in the range of 16,90–17,89%) justify the approach for analysis and optimization of a monosymmetric box cross-section of the main girder of a double girder bridge crane for the observed optimization example. Also, it can be noticed that the required number of diaphragms is smaller (Table 2) for the example of the existing solution of a bridge crane.

Fig. 3 and Fig. 4 show that the optimization procedure should be repeated several times (ten simulations) since significantly higher values than expected were obtained. The reason for this is a large number of variables and constraint functions.

The presented methodology of optimal design to achieve low-weight structures, and the application of the LAPO algorithm, enables the implementation of this procedure for similar types of carrying structures, where many optimization variables and constraint functions can be applied.

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Table 1. Optimization results for both types of material.

Steel	t (cm)	s (cm)	b_1 (cm)	h (cm)	m	n	m_l (cm)	n_l (cm)	t_l (cm)	best (kg)	worst (kg)	mean (kg)	Std
S355	1,298	0,654	41,314	129,833	1,641	0,258	7,208	2,500	0,556	5714,6	7046,3	5760,9	134,8
S275	1,239	0,691	44,822	128,070	1,848	0,260	6,927	2,502	0,534	5899,1	7435,9	5946,5	149,8

Table 2. Rounded values of optimal geometric parameters, weights of the main girder, and savings in material.

Steel	t (cm)	s (cm)	b_1 (cm)	h (cm)	n_d	m_l (cm)	n_l (cm)	t_l (cm)	M_o (kg)	Savings (%)
S355	1,3	0,7	41,3	129,8	11	7,2	2,5	0,6	6009,718	17,89
S275	1,3	0,7	44,8	128,1	9	6,9	2,5	0,6	6082,400	16,90