APPLICATION OF GENETIC ALGORITHM IN DESIGN OF ARCH BRIDGE

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Summary: *Topic of this article is application of Genetic Algorithm (GA) as a method of global optimization for determining characteristic dimensions of arch concrete bridge. Implementation of genetic algorithm for designing elements of an arch bridge with assign static scheme, span and quality of material is conducted in software Matlab. Goal of this application is to determine dimensions of cross-section and rise of concrete arch with minimum use of material and with carry out stress control in characteristic cross sections.*

Keywords: *Genetic algorithm, arch bridge, concrete, Matlab*

1. INTRODUCTION

Optimization is part of life each of us. Aim of every natural process is using optimal ways to finish tasks with minimum using of energy with the best results. In the modern world, this concept can apply in economy, industry, finance, communications and other branches. The concept is to choose the solution from the domain of possible, which gives the best results with minimum consumption of resources and carry out initial conditions and constraints. Methods of global optimization are powerful tools for this achievement.

Genetic Algorithm (GA) as a method of global optimization has found application in different economy and industry branches to choose the best solution in solving of problems. Civil engineering is main part of economy every country and good place to apply global optimization. In the last years, a lot of science journals and studies was written about successful application genetic algorithm in civil engineering. GA has achieved a remarkably save of resources and time necessary for design process.
Some authors have shown successful application genetic algorithm on bridge design. Genetic algorithm has been used for determination of optimal dimension of cross section

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bridge deck for input data such as: span, static scheme, loads and stress constraints. Goal function was to minimize construction volume. [1], [5]
Also, genetic algorithm is applied for structural engineering. M.G. Sahab and others [14] used hybrid genetic algorithm for design optimization of flat slab building. Goal function was total costs which include costs of concrete, formwork, reinforcement and foundations. Aim was to minimize total cost with carry out resistance constraints. On that way it was possible to reduce total cost of building with adequate resistance and serviceability.
Hence, based on this results genetic algorithm is used more and more for structural damage detection in buildings and bridges. Sahu and Nayak used genetic algorithm for founding the damage location in construction elements (such as crack) with vibration analysis and finite elements methods. [15]. Also combination of genetic algorithm with vibration analysis is used to determine damage scenario on railway bridge [2]. Genetic algorithm is successfully used for optimal design of cross section elements in construction and also used for fibre composite structures [13].

2. THE GA PROCEDURE

Genetic algorithm belongs to stochastic methods of global optimization. Main idea of genetic algorithm as a search heuristics is imitation natural selection. That is reason for using terms from natural selection like a individual, population, selection, crossing, mutation in algorithm process.

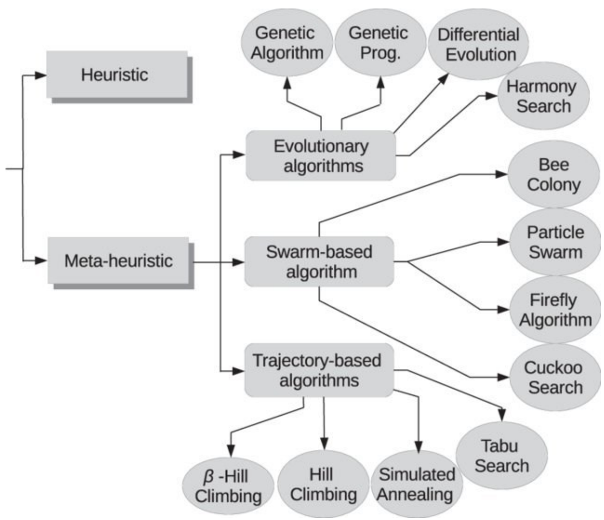

Figure 1. Type of optimization algorithm [16]

Creator of genetic algorithm is professor John Henry Holland. In his book Adaptation in Natural and Artifical Systems [8], he set fundamental principles of genetic algorithm and his application. Many authors call this algorithm as a canonic or simple genetic algorithm.[10 19 20].

Functioning of genetic algorithm is provided by individual population, usually from 10 to 200, where each individual is potential solution for considered problem. Individuals are coded by binary system (0 and 1). Quality of individual is provided by fitness function. Adaptation improvement for individuals in genetic algorithm is made by selection operator, crossing and mutation. On this way, better solutions are created than previous. [19 20 21] Some authors call individuals by children, whereby individuals which make new children call parents.

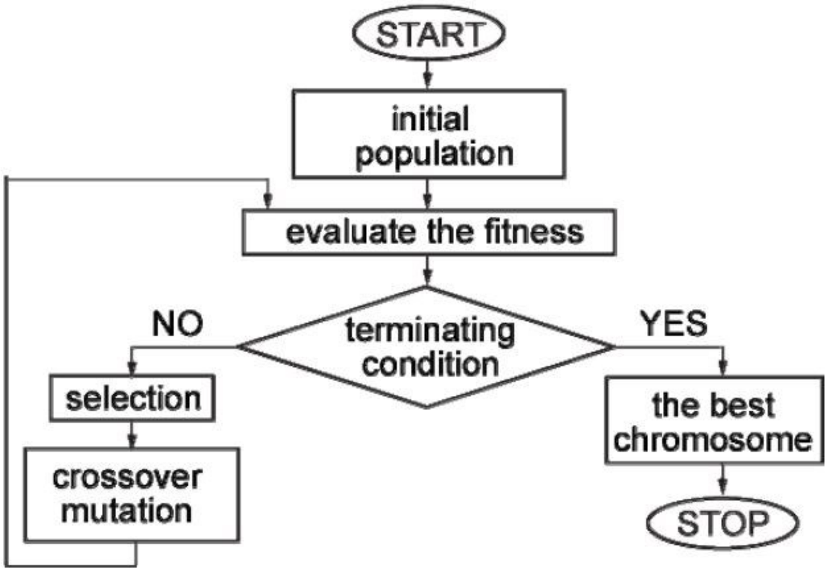

Figure 2. Scheme of genetic algorithm [9]

Main principle of genetic algorithm is creating new individuals in considered space by algorithm operators using existing individuals, until occurrences of individuals satisfying adaptation. This individuals are the best solutions of considered problem. [4 10 19 20 21]. For the last 50 years genetic algorithm has been used in various applications: civil engineering, economy, medicine, machine learning, mathematics, computer science, finance, biology and other. In the future, it is expected to have more and more applications of genetic algorithm in all branches of economy, especially in civil engineering. Saving time and resources will be main tasks in modern civil engineering, and that will be the main driving force for more and more application of genetic algorithm as a method global optimization.

3. BASIC OF ARCH BRIDGE

The arch as a static scheme of bridge developed 3000 years before new age. First arch and vault was made from mud and cane with maximum span 3.60 m on the territory delta Tigre and Euphrates for making house [12]. First arch stone bridges were made and used on famous "Roman roads" in Roman empire. During renaissance period there was not significant development of arch bridges. The great development of arch bridge was started at the beginning of 20 centuries by three great constructors and research: Francois Hennebique, Robert Maillart and Eugene Freyssinet. They set up basic principles for design and building arch bridge which apply till today.

Figure 3. Pont du Gard Bridge, France (1st century AD) [26]

Wanxiang (*Figure 4*) with span of 420 m is the world recorder. Span of arch concrete bridge is depended by static scheme as a two – hinged arch, three – hinged arch and fixed arch. Also, typical elements of arch concrete bridge are intrados, extrados, wall, columns and slab.

Figure 4. Wanxian bridge, Wanzhou, Chongqing, China (1997.) [25]

What makes arch system special is that the bending moments depend on the shape of arch axis. Also, the values of flexural moments increase with the number of joints, where the horizontal pressures have approximately same value. Arch concrete bridges are sensitive on parasitic actions such as a temperature and movement of supports. Numerical analysis of arch concrete bridges in the past, showed some facts as a: [11]

- Bending moments from movement of supports increase with stiffness of arch, span and reduction of rise,
- Bending moments from temperature are proportional to stiffness, inversely proportional to rise and independent from span,
- By increasing of span with same span/rise ratio include lower stress from parasitic actions, so rigid arch can be adopted for larger spans.

Experiential recommendations for dimensions of full rectangular cross-section in arch concrete bridge are: [10]

1. span: L= 40-100 m,
2. height: h= L/60 - L/100 m,
3. width: b= L/15 m,
4. rise: f= L/2 – L/10 m, where is L span of arch.

4. OPTIMIZATION OF CONCRETE ARCH BRIDGE

Arch concrete bridge (*Figure 5.*) with fixed span of 60 m is considered in the paper. The focus was on the arch, with main structural elements on this type of concrete bridge. In this analysis, it wasn't considered slab, columns and other elements. In order to simplify design and analysis, it was adopted that approximate load transfer from slab is transposed on concrete arch.
Static scheme of considered bridge is fixed arch with span of 60 m. Adopted load on the bridge is from motorway I order with two lanes and two pedestrian trails. Total width of the bridge is 12.10 m, where width of motor lanes is 7.00 m. Cross-section of considered bridge is reinforced rectangular b x h with constant dimension lengthwise. Material is reinforced concrete C 30/37 according to [18].

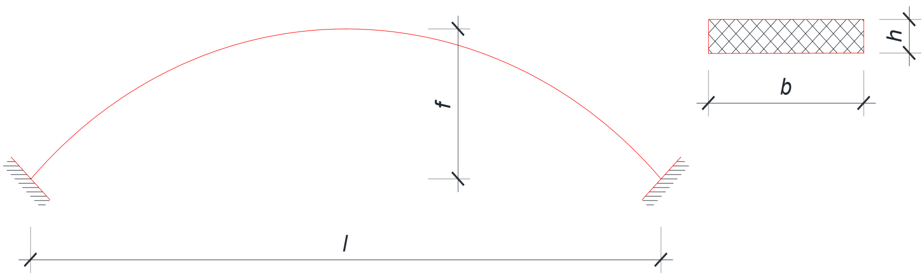

Figure 5. Considered concrete arch

The following loads and actions on the concrete arch are taken into account:

1. Self-weight, determined as a volume mass of arch multiplied density of concrete (γ=25 kN/m^3),

2. Dead load from asphalt layer and hydro isolation, also layer on pedestrian trails, barrier for noise and wind, and others,
3. It was used LM1 case of traffic loads according to [18],
4. Temperature.

4.1 Problem formulation

Volume of arch defined by length of arch, width and height of cross-section is adopted as goal function "fun" (1). Design constraints are introduced in total goal function "F" through the second, penalty part of the function. It is used for rejection of bad solutions which didn't carry out limitations. Penalty part of this function "pen" (2) represents maximal value of differences between stress in considered section and design constraints according to Eurocode 2 [18]. This part was multiplied by penalty factor "c_p" which gives significance to penalty part in the goal function. Aim was minimizing goal function, through optimization process, in order to obtain solution that requires minimal volume of the arch (least cost) necessary to carry out design constraints.

$$F = -(fun + c_p \cdot pen) \tag{1}$$

$$\begin{aligned}
pen &= \max(dsigma1, dsigma2, dsigma3, dsigma4, dsigma5, dsigma6) \\
dsigma1 &= \sigma_{o,rare1} - 18000 \\
dsigma2 &= \sigma_{o,rare2} - 18000 \\
dsigma3 &= \sigma_{o,qp} - 13500 \\
dsigma4 &= \sigma_{s,rare1} - 18000 \\
dsgima5 &= \sigma_{s,rare2} - 18000 \\
dsigma6 &= \sigma_{s,qp} - 13500
\end{aligned} \tag{2}$$

Also, it was defined D/C ratio (Demand/Capacity ration in % which should be less or equal than 100%):

$$\begin{aligned}
D/C = \max(&abs(dsigma1), abs(dsigma2), abs(dsigma3), abs(dsigma4), \\
&abs(dsigma5), abs(dsigma6))
\end{aligned} \tag{3}$$

In equation (2), "o" means section on support and "s" means section in the middle of span.

4.2 Design variables

Three basic variables are used in optimization process:

1. Arch rise f – with local constraint: $6<f<15$ (4)
2. Height of cross-section h - with local constraint: $0.5<h<2$ (5)
3. Width of cross-section b –with local constraint: $4.5<b<8$ (6)

Hence, three variables were coded in binary system (0 and 1). 8 binary bits are used for each variable, therefore total length of binary strings for coding is 24 binary bits.

4.3 Design constraints

Compressive stress was considered as design constraint according to Eurocode 2 [18] in 7.2.2 and 7.2.3 for characteristic (rare) and quasi-permanent (qp) combination of loads:

$$\sigma_{rare} \leq 0.60 \cdot f_{ck} \tag{7}$$

$$\sigma_{qp} \leq 0.45 \cdot f_{ck} \tag{8}$$

where f_{ck} is characteristic compressive strength.

Stress constraints were considered in both characteristics section – middle of span and support for both combination of loads. Constraints were introduced in goal function within penalty part “pen” and multiplied with penalty factor “c_p”.

4.4 Result of optimization

For optimization with genetic algorithm in this paper was used Matlab programme add in “EPALG”. EPALG graphical user interface allows entering input parameters such as: number of generations, population size, length of coded solution, mutation rate, crossover rate and type etc. (shown on the left part of Figure 6). Right part of user interface is reserved for graphical representation of optimization process with the best results (optimal value of goal function) [19].

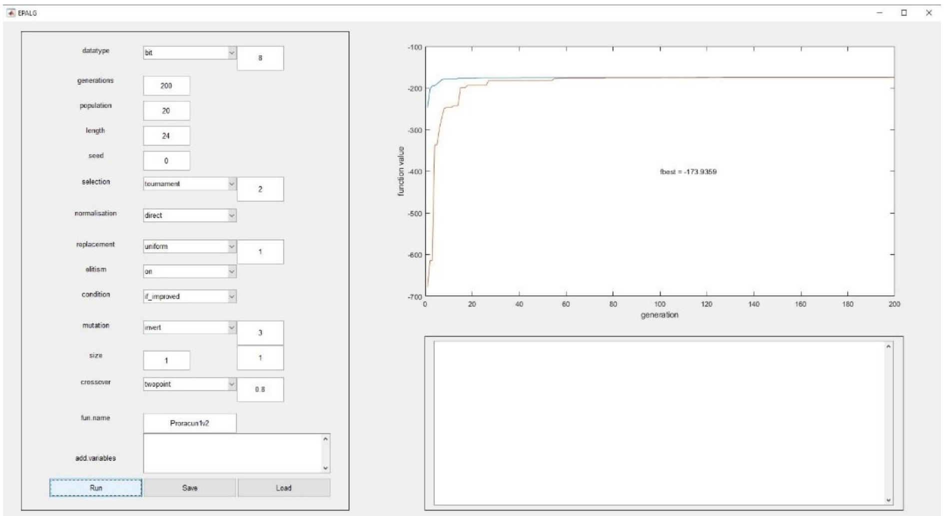

Figure 6. Screen show of „EPALG“ programme

During optimization process several different cases were considered (Table 1). GA input parameters that are varied are: population size, mutation rate, value of crossover rate and others. Also, it was changed value of penalty factor “c_p”. These comparative results are summarised through the cases below. For all noted cases and variation of input parameters, shown in following tables, values of: design variable (Arch rise f - x(1), Height of cross-section h - x(2) and Width of cross-section b – x(3)), goal function (F) and D/C ratio.

Table 1. Cases for comparative studies in optimization

Number of Case	Description
Case 1	Variation number of generations – 10, 50, 100, 200 or 1000
Case 2	Variation number of population – 10, 20 or 100
Case 3	Variation of selection type – roulette or tournament
Case 4	Variation of mutation rate – 1, 2 or 3
Case 5	Variation of crossover type - one point or two point
Case 6	Variation of penalty factor “cp” (0, 0.001, 0.01, 0.05, 0.1, 1, 10 ,100)

Table 2. Input parameters and result of optimization with D/C ratio for Case 1

Gener.	Popul.	Selec. type	Mutation rate	Cross. type	c_p	fun [m^3]	x(1) [m]	x(2) [m]	x(3) [m]	D/C ratio [%]
10	20	Tour.	3	2point	0.05	**178.79**	8.27	0.58	4.80	98.68
50	20	Tour.	3	2point	0.05	**173.07**	8.96	0.60	4.52	99.96
100	20	Tour.	3	2point	0.05	**172.61**	8.47	0.60	4.54	100
200	20	Tour.	3	2point	0.05	**173.93**	8.51	0.59	4.66	100
1000	20	Tour.	3	2point	0.05	**172.61**	8.47	0.60	4.54	100

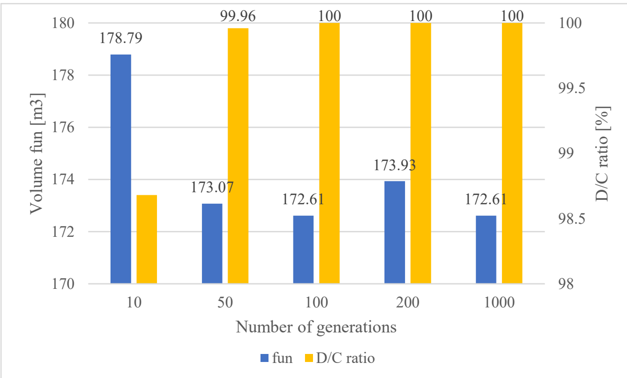

Figure 7. Results of optimization for Case 1

Table 3. Input parameters and result of optimization with D/C ratio for Case 2

Gener.	Popul.	Selec. type	Mutation rate	Cross. type	c_p	fun [m^3]	x(1) [m]	x(2) [m]	x(3) [m]	D/C ratio [%]
200	10	Tour.	3	2point	0.05	172.55	8.40	0.61	4.50	99.87
200	20	Tour.	3	2point	0.05	173.93	8.51	0.59	4.66	100
200	100	Tour.	3	2point	0.05	172.61	8.47	0.60	4.54	100

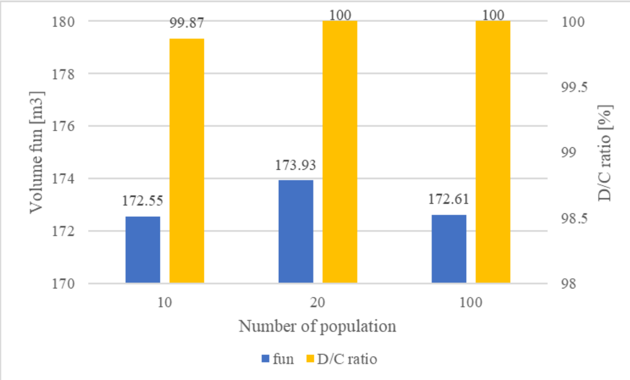

Figure 8. Results of optimization for Case 2

Table 4. Input parameters and result of optimization with D/C ratio for Case 3

Gener.	Popul.	Selec. type	Mutation rate	Cross. type	c_p	fun [m^3]	x(1) [m]	x(2) [m]	x(3) [m]	D/C ratio [%]
200	10	Roul.	3	2point	0.05	**174.67**	8.51	0.58	4.73	**99.95**
200	20	Tour.	3	2point	0.05	**173.93**	8.51	0.59	4.66	**100**

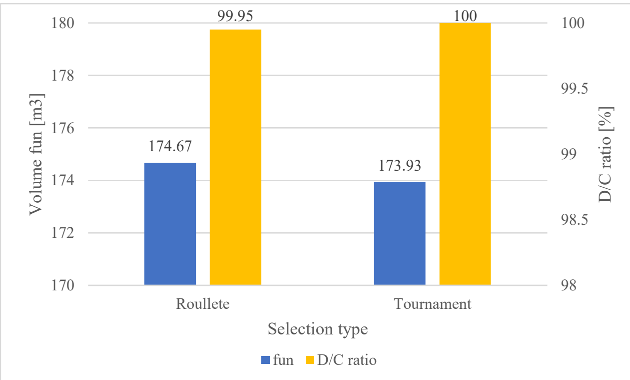

Figure 9. Results of optimization for Case 3

Table 5. Input parameters and result of optimization with D/C ratio for Case 4

Gener.	Popul.	Selec. type	Mutation rate	Cross. type	c_p	fun [m^3]	x(1) [m]	x(2) [m]	x(3) [m]	D/C ratio [%]
200	20	Tour.	**1**	2point	0.05	**176.74**	8.47	0.56	4.93	**100**
200	20	Tour.	**2**	2point	0.05	**175.35**	8.11	0.62	4.50	**99.93**
200	20	Tour.	**3**	2point	0.05	**173.93**	8.51	0.59	4.66	**100**

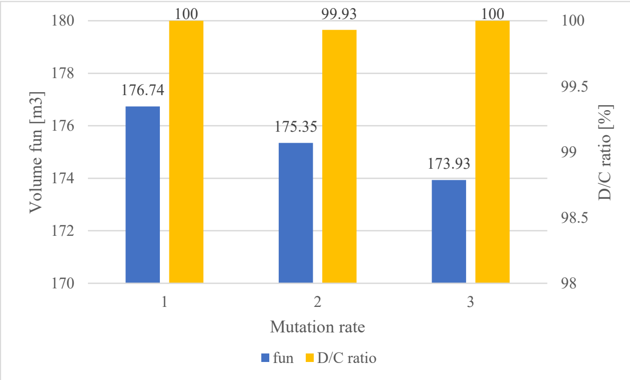

Figure 10. Results of optimization for Case 4

Table 6. Input parameters and result of optimization with D/C ratio for Case 5

Gener.	Popul.	Selec. type	Mutation rate	Cross. type	c_p	fun [m^3]	x(1) [m]	x(2) [m]	x(3) [m]	D/C ratio [%]
200	20	Tour.	3	1point	0.05	**172.72**	8.54	0.60	4.54	**99.93**
200	20	Tour.	3	2point	0.05	**173.93**	8.51	0.59	4.66	**100**

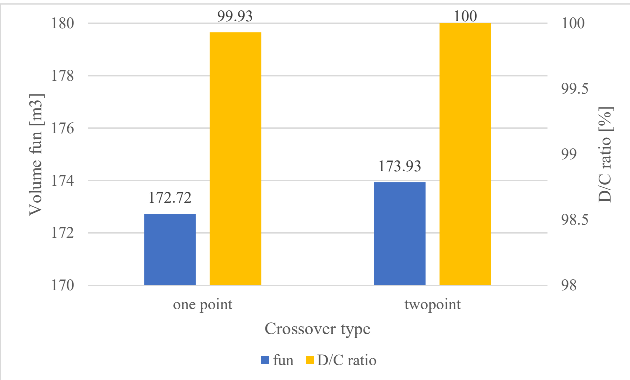

Figure 11. Results of optimization for Case 5

Table 7. Input parameters and result of optimization with D/C ratio for Case 6

Gener.	Popul.	Selec. type	Mutation rate	Cross. type	c_p	fun [m^3]	x(1) [m]	x(2) [m]	x(3) [m]	D/C ratio [%]
200	20	Tour.	3	2point	0	**139.01**	6	0.5	4.5	**100**
200	20	Tour.	3	2point	0.001	**142.11**	8.22	0.5	4.5	**100**
200	20	Tour.	3	2point	0.01	**171.96**	8.57	0.59	4.50	**100**
200	20	Tour.	3	2point	0.05	**173.93**	8.51	0.59	4.66	**100**
200	20	Tour.	3	2point	0.1	**173.95**	8.54	0.59	4.66	**99.98**
200	20	Tour.	3	2point	1	**173.95**	8.54	0.59	4.66	**99.98**
200	20	Tour.	3	2point	10	**173.95**	8.54	0.59	4.66	**99.98**
200	20	Tour.	3	2point	100	**173.95**	8.54	0.59	4.66	**99.98**

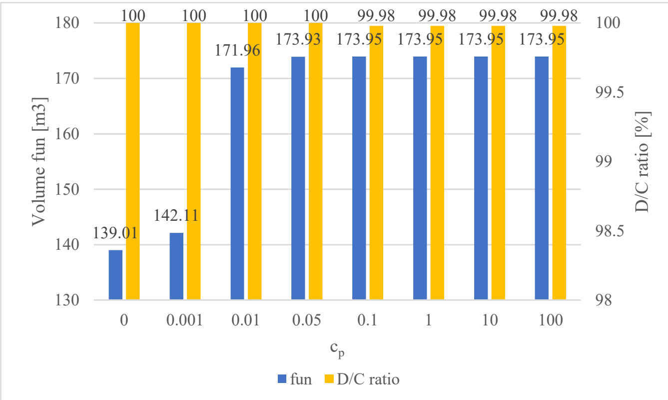

Figure 12. Results of optimization for Case 6

5. DISCUSION AND CONCLUSIONS

Based on the results of the optimization with genetic algorithm, the following conclusions and recommendation for future work are drawn:

- Genetic algorithm is powerful tools which allows rapid and simple way for finding the best solution, which can serve as starting point in design of structures;
- In this optimization a lot of simplification was used as a modeling, transfer and value of loads. Because, main element (considered arch) was separated from the structures which works like a one entirety;
- Constraints have an important effect on optimization results. Lower range of width of cross-section applied, will give lower volume of arch or total costs, but this isn't possible because that optimization solution is not according with

technology of construction and connection substructure (considered arch) with superstructure (bridge deck slab and columns) of bridges;

- Results in Table 2-7 has shown that GA is robust optimization method so that change of input parameters don't affect value of goal function "fun" which is volume of considered arch and hence total goal function "F" and D/C ratio. Differences in obtained results isn't more than 5%, expect in Case 6 with changed value of penalty factor "c_p";
- Based on all results, it can be possible to make main conclusion of this paper: aim of genetic algorithm application is find solution which included maximum or minimum of goal function with carry out of initial conditions and constraints. In considered problem, the goal was to find minimum of arch volume with carry out of design constraints. EPALG gives the best solution which include the smallest value of arch volume with D/C ratio of 100% or very close to that value. This design approach isn't suitable for considered structures, because in design of structures we usually want to have some reserve in D/C ratio (30-50%), which provides that structures could be safely used after some changes in value of loads or others effects (changing traffic intensity on route where is bridge).

Clearly there is a trade off in design of structures that involves two aspects: investment or expenses on the one side and risk and adaptability in uncertain future usage of the structure on the other.

Recommendation for future work is application of other optimization tools on considered problem, which is more suitable for design of structures such as NSGA II (Nondominated Sorting Genetic Algorithm II) [24] which represents multi objective genetic algorithm. Aim is to find more optimal solutions which all satisfy initial conditions and constraints, and to select a set of non dominant solutions according to two previously mentioned criteria: expenses and adaptability (Figure 13). This way is more suitable to use in design construction, because we can make connection between function objectives (in considered problem that was volume of arch and D/C ratio). In the future it can be expected paper from this topic.

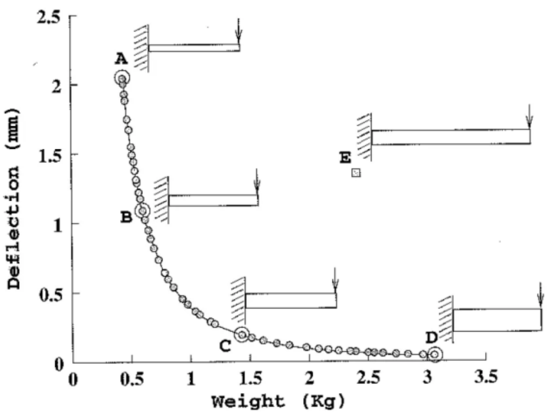

Figure 13. Application example of NSGA II algorithm for optimization [27]

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ПРИМЕНА ГЕНЕТСКОГ АЛГОРИТМА У ОДРЕЂИВАЊУ ДИМЕНЗИЈА ЛУЧНОГ МОСТА

Резиме: *Тема овога рада је примена генетског алгоритма (GA) као методе глобалне оптимизације за потребе одређивања карактеристичних димензија лучног бетонског моста. За лучни мост задатог статичког система, распона и квалитета материјала показана је примена прорачуна оптимизације са алатима генетског алгоритма (GA) у софтверском пакету Matlab. Циљ прорачуна је одређивање димензија попречног пресека и стреле бетонског лука са којима се остварује најмањи утрошак материјала уз задовољење напонских услова у карактеристичним пресецима.*

Кључне речи: *Генетски алгоритам, лучни мост, бетон, Matlab*