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Genetic Algorithm to optimize the strategies for bridge repair works

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Abstract

An approach to solve the problem of reducing the operating costs and increasing the residual life of highway bridges is showed in this article. The main goal of this study is to optimize a lifecycle model of highway bridge's elements using a special type of genetic algorithm (GA). GA allows managing the residual life of highway bridges. The goal is achieved by performing the following tasks: developing a degradation model of bridge elements; developing a model for the definition of bridge performance measures costs at the network level; optimizing the lifecycle of the bridge's elements using GA. A special high-speed GA was developed and designed for working with the Ukrainian Bridge Management System (AEBMS). The developed GA differs from the traditional GA. For example, the GA takes into account the peculiarities of the allowable sequence of various repair works depending on the degree of the bridge's degradation and the steps which were taken during the previous years.

Keywords: highway bridges; lifecycle model; genetic algorithm; Bridge Management System

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1. Introduction

In 2004, "DerzhdorNDI" SE together with the National Transport University started to develop an Analytical Expert Bridges Management System (AEBMS) - the main tool of Ukrainian bridges exploitation system on public roads for the purpose of centralized storage of information on the bridges monitoring state for maintaining them in safe exploitation state. The basis for the creation of the AEBMS was the model for estimating and predicting the operational state of bridges, proposed in the works of Professor Lantuch-Lyashenko, A.I. (for example, 1999, 2009).

The AEBMS software complex is used at all levels of Ukravtodor's (State Road Agency of Ukraine) management, dynamically developed and complemented by new analytical functions and is constantly updated with new data from the surveys of the bridges.

The AEBMS software complex contains detailed data on the bridge as a whole and its main elements, and due to the grouping system by regions, districts, roads of administrative importance, road sections within the region and district, the complex is used as a network level system.

In total, the system covers 16 150 bridges, 5 500 of which were surveyed and their exploitation state was determined. At present, the information on 70% of the bridges on the roads of state importance and 15% on the roads of local importance are included in the AEBMS database. The main parameters of the bridges (location, obstruction, width, length, year of construction, etc.) which survey is not conducted yet are also included in the database.

The reports of Ukravtodor both, the regulations and the reports in arbitrary forms are generated based on the data provided by the surveys using numerous filters and types of grouping.

Some basic analytical functions of the AEBMS are the following: an expert assessment of the exploitation state of the bridge, prediction of the residual life of the structure, the analysis of the compliance of the exploitation characteristics of the bridges with the regulatory requirements, ranking of bridges by repairs need (reconstruction), formation of current and task plans of inspections, repairs, issuing the recommendations of exploitation strategies and planning the financial resources for reconstruction, repairs and exploitation maintenance of bridges.

The task of effective management of bridge's repairs and reconstruction is of key importance. It is a common knowledge that untimely repairs lead to a significant increase in the costs allocated for the restoration of exploitation state of bridges.

The development of the strategy of the bridge's repair is a complex scientific task, effective solving of which requires the use of current novel models and algorithms and, in the first place, - effective algorithms of mathematical optimization.

Taking into account the large dimension and the combinatorial nature of the task, it is appropriate, as the analysis of scientific literature sources shows, to apply a genetic algorithm (hereinafter - GA) of optimization of the bridge's repair strategy, the core idea of which is described in this study. This algorithm is based on the approach proposed by Liu Chunlu et all (1997) for single-objective optimization and Liu Chunlu (2005), Hrstka O. et all (2003), Patidar V. et all (2007) for multi-objective optimization.

The main purpose of the study is scientific research of a model for optimization of the bridges lifecycle at the network level based on the use of a special-type GA.

This purpose is achieved by performing the following tasks:

- development of a model of bridge's elements degradation;
- development of an evaluation model of the cost of exploitation measures at the network level;
- optimization of the life cycle of the bridge's elements using the GA method.

2. The model of bridge's elements degradation

The model of the bridge's elements degradation is required to monitor the changes of the indicators that characterize the current state of the structure or its individual elements (reliability, degradation level, residual life) in time (in the process of "aging") and taking into account the impact of the conducted exploitation measures. The elements of the bridge are combined in seven groups (DSTU-N B.V.2.3-23:2012): bridge decking, bridge spans, bridge bearings, foundations, regulatory facilities, entrances to the bridge, channels.

A quantitative indicator of an expert assessment of the exploitation (or discrete) state of the bridges is a formalized expert assessment - a rating that serves as an indicator for the classification of the structure's exploitation state and the scheduling certain exploitation measures (Table 1).

Table 1. Classification of the exploitation states of the structure and general characteristics of the state depending on the rating

State No.	State Name	Rating, from-to	General characteristics of the state
1	Serviceable	100-95	Routine inspection and maintenance are performed
2	Limitedly serviceable	94-80	Routine inspection, maintenance and current repair are performed without traffic restriction
3	Workable	79-60	Routine inspection is performed, intervals between periodic inspections are reduced, and current repair is performed. Traffic speed is restricted if required
4	Limitedly Workable	59-40	Inspections by special schedule are conducted and overhaul is performed. According to defects of structures, the traffic of vehicles is restricted by weight, speed and dimensional parameters. If required, special measures to ensure the no-failure operational of the bridge are being developed.
5	Non-Workable	≤ 39	Constant supervision and control over the implementation of traffic restrictions with the involvement of a specialized organization are performed. Urgent resolution of the issues on the reconstruction of the structure or its closure. Interim measures are taken to prevent the accident

As a result of the survey of the bridge's elements, the group state is assigned by the weakest element. The indicator of reliability and the level of degradation conform to each exploitation state (Table 2). The level of degradation is accepted as a dimensionless quantity that takes the value in the range of $D \in [0.1]$, where D is the level of degradation. Zero point is a lack of degradation, and point one the accident corresponds to the collapse of the bridge's element.

Table 2. Boundary values of the degree of degradation and reliability regarding exploitation state.

Exploitation state	Degree of degradation (D) $D_{i,н} \leq D < D_{i,н}$	Reliability by the first group of the boundary state, $Pi,в \leq P < Pi,н$
State 1	$0.00 \leq D < 0.05$	$0{,}999844 \leq P < 0{,}998363$
State 2	$0.05 \leq D < 0.20$	$0{,}998363 \leq P < 0{,}992461$
State 3	$0.20 \leq D < 0.40$	$0{,}992461 \leq P < 0{,}979771$
State 4	$0.40 \leq D < 0.60$	$0{,}979771 \leq P < 0{,}958351$
State 5	$0.60 \leq D < 1.00$	$0{,}958351 \leq P$

Bridge repairs increase the reliability of the bridge's element and, thus, reduce the level of degradation D. For the model's development it is simplified: only one of five types of measures is performed in the current year: exploitation maintenance, current minor repair with maintenance, current midterm repairs, overhaul, reconstruction (new construction), or no measures to be taken.

According to the research conducted by Liu et all and after the adaptation of obtained data, the following impact values were applied on the basis of the analysis of actual data accumulated in the AEBMS, per each type of repair, as well as per exploitation maintenance types (table 3).

Table 3. Impact of maintenance and repair activities on the reduction of a degradation level

Activity	Impact
Do nothing	0.00
Routine maintenance	0.01

Current minor repair & Routine maintenance	0.05
Current midterm repair	0.40
Overhaul	0.90
Reconstruction	0.97

The type of the activities for the structure in compliance with its state is selected randomly each year by the Monte Carlo method basing on the given alternatives, as shown in Figure 1.

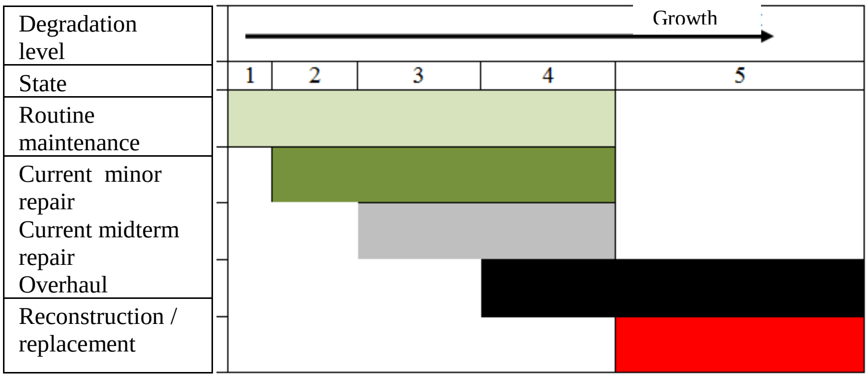

Fig. 1 Alternative types of work depending on the exploitation state

Degradation model will be the following:

$$D(T) = D(0) + \sum_{t=1}^{T} \Delta D(t) - \sum_{t=1}^{T} I_m(t), \tag{1}$$

where: T – planned period of strategy, years;

t – current year;

$D(T)$ – degradation level at the end of a planned period;

$D(0)$ – degradation level at the beginning of the period;

$\Delta D(t)$ – increasing of the degradation level during the year t;

$I_m(t)$ – impact of repair measure (m) on reduction of degradation level in a t year.

The degradation model establishes a connection between the reliability and the operation time of the element. The transition from one discrete state to another is described as a Poisson process with discrete states and continuous time. This is a special case of the Markov process. The integral distribution function $P(t)$ for the time T_n, which proceeds until all n events of the process occur, has the form:

$$P(t) = 1 - P(T_n > t) = 1 - \sum_{k=0}^{n-1} \frac{(\lambda t)^k e^{-\lambda t}}{k!}, \tag{2}$$

where $P(t)$ is the probability that the element will go to state k for time t < Tk;

t - time (age of structure);

λ - parameter of the process - the intensity of failures;

k - exploitation state number;

e - base of the natural logarithm, e = 2,718;

For a case of a linear graph (Figure 2) of five discrete states (S_1, S_2, S_3, S_4, S_5; i.e. k = 5), the dependence (2) has the form:

$$P(t) = 1 - \frac{(\lambda t)^5 e^{-\lambda t}}{5!} = 1 - 0.008333 \cdot (\lambda \cdot t)^5 \cdot e^{-\lambda \cdot t} \cdot, \text{i.e} \ \frac{1}{5!} = 0.008333. \qquad (3)$$

Thus, with a given intensity of failure, the dependence (3) establishes the relationship between the reliability of the element *P(t)* in the *i*-th state and the time t, which has passed from the beginning of operation to the state *i* = 2, ... 5.

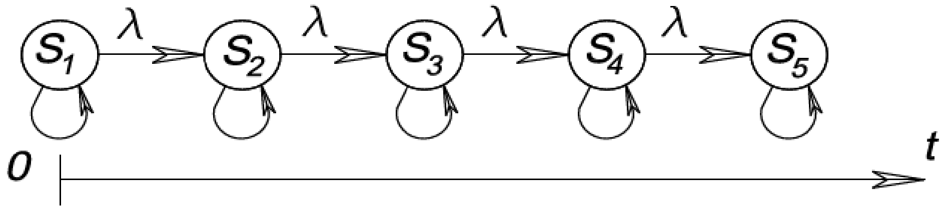

Fig. 2 Graph of the degradation process

3. Network model of assessment of the structure's life cycle cost

The task of the bridge's repair strategy optimization is considered at the network level and it represents NP-complete combinatorial task of discrete optimization, and in conditions of limited budget – a knapsack problem.

The mathematical model of the bridges exploitation state optimization on a highways network in conditions of limited funding has two target functions (optimization criteria):

- average annual for T period and average weighted by the area of bridges degradation level on the Z_s road network with a unit of year^{-1} (formula 4);
- The penalty function of the cost of the work program Z_C (formula 10).

Target function Z_S - average annual for T period, average weighted by the bridges square degradation level

To minimize

$$Z_S = \frac{1}{(T+1) \cdot \sum_{i=1}^{N} A_i} \cdot \sum_{i=1}^{N} \left(IF_i^{-1} \cdot A_i \cdot \left(D_{i,0} + \sum_{t=1}^{T} D_{i,t}(X_{i,t}) \right) \right) => \min, \qquad (4)$$

where: N – number of bridges;
T – number of years;
A_i – the area of *i*-th bridge, m^2;
$D_{i,0}$ – the initial level of degradation of *i*-th bridge;
$D_{i,t}$ – degradation level of *i*-th bridge at the end of *t* year;
$X_{i,t}$ – variable of the decision that takes value from a plurality of work types, $X_{i,t} \in \{0,..,5\}$;
IF_i – factor of importance of the *i*-th bridge;

with restrictions:

reliability restriction

$$1 > P_{t,i} \geq 0.9500, \tag{5}$$

or degradation level restriction

$$D_{t,i} \leq D_{\max}, \forall D_{t,i} \tag{6}$$

where: D_{max} – the maximum acceptable degradation level. This restriction can be violated if there is insufficient funding;

budget limitation of the cost of repair and maintenance of all bridges of the network in t year

$$C(t) = \sum_{i=1}^{N} C_{t,i,m} \leq B(t), \forall t, \tag{7}$$

where: $C_{t,i,m}$ – cost of activity m for *i*-th bridge at the year *t*;

B(t) – budget of program at the year *t*. This restriction cannot be violated;

restriction of the maximum allowable degradation level:

$$D_{\max} \leq D_{MP}, \tag{8}$$

where: D_{MP} – the maximum permissible degradation level.

The limit degradation level can be taken as a constant value at practical application:

D_{MP} is constant. (9)

Optimization by the criterion of the cost Z_C of repair for the strategic period of time T is performed by the penalty method s (measured in thousands UAH). Accordingly, the target function is written in the following form:

$$Z_C = \sum_{i=1}^{N}\sum_{t=1}^{T} C_{t,i} \cdot \left(1 + \sum_{i=1}^{N}\sum_{t=1}^{T} \max\left(\frac{D(t,i,X_{t,i}) - D_{\max}}{D_{\max}}, 0\right)\right) => \min, \tag{10}$$

where Ct,i – the cost of repair and maintenance of i-th bridge in a t year, discounted at the real rate by the formula Irving Fisher, thousands UAH;

D_{max} – non dimensional maximum allowable degradation level.

So, the target function is the sum of the cost of repairs, maintenance of bridges and of penalties. When the given maximum allowable degradation level is exceeded, the value of the function which serves as a barrier for unjustified reduction of the cost of bridge repairs will increase. Exceeding of the maximum allowable (D_{max}) bridges degradation level is evaluated taking into account the penalties. It is determined on the basis of economic justification but cannot be worse than the limit degradation level (D_{MP}) of the requirements of traffic safety and preservation of an element (formula 8).

It should be noted that in the first instance, the design estimates on the bridges that require repairs can be obtained during the year of the bridges restoration program initiation, therefore $C_{t,i}$ is the cost of the repair of the *i*-th bridge in a *t* year is selected from the consolidated estimated calculation. In the case where the design estimates are not available, an aggregate index of work costs is to be used.

4. Optimization of the bridge's elements life cycle by the GA method

A special GA was developed within the research that is adjusted to the work with the AEBMS database. It is different from the classic one as it takes into account the features of the allowable sequence of activities implementation which depends on the bridge's degradation level and earlier scheduled exploitation measures and verification of their feasibility under financial constraints.

The chromosome (one solution from the population) consists of *N* sections according to the number of bridges, each of which consists of *T* genes by the number of years in the planning period (see Figure 3). The value of the gene is do-nothing, routine maintenance, repair or replacement activities code (Table 3), which is not coded into a bit string, as is used by Liu Chunlu et all (1997). This is quite acceptable, according to Rutkovskaya D. et all (2006). Activities method at any year will be selected from suitable methods semirandomly considering maximum allowable deterioration degree as with Liu Chunlu et all (1997), (see Figure 1). The selection operator is tournament selection. It should be noted that the points of chromosome rupture for the execution of the crossover operator can not be located inside the bridge section, but only between the sections. The gene mutation operator is performed by selecting its new value by the Monte Carlo method taking into account the constraints (Figure 1), as well as the limitations of the mathematical model.

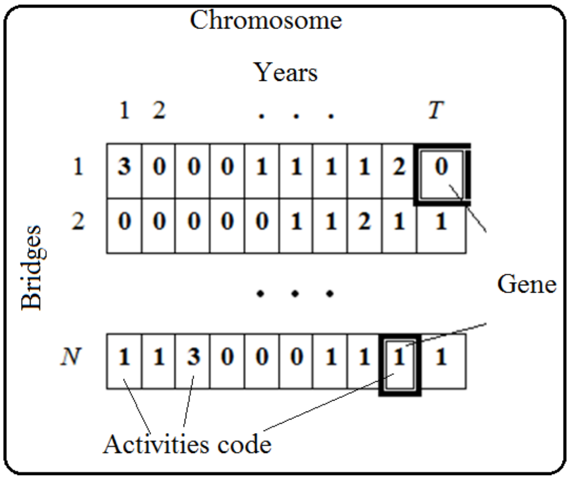

Fig. 3 Structure of the chromosome - one solution from the population

The GA software module is included in the AEBMS as a practical tool of bridge's repair and maintenance management.

The use of the developed algorithm within the framework of AEBMS has proved its adequacy to the assigned tasks and the high efficiency for the search of the optimal decision. The search of the optimal cost value is performed in a short time and has consistent convergence.

Figure 4 shows a graphical interpretation of the optimal search process in the AEBMS software system. It shows how the optimization process goes on and the number of cycles to achieve a stable value.

The result of optimization is a program of repairs for the bridge network for a given period with the detailing the types of repairs for each bridge per each year of the strategy and the estimated cost of works and the degradation level at the beginning and the end of the year as well as with the bridge's state change (Table 4).

The developed program module in the AEBMS allows for each generated strategy to receive a graph of the distribution of financial resources for repairs, the graph of changes of the averaged average weighted by years of degradation (Figure 5), the graph of change of the averaged average weighted by the years of the rating and the diagram of cost distribution by repairs types.

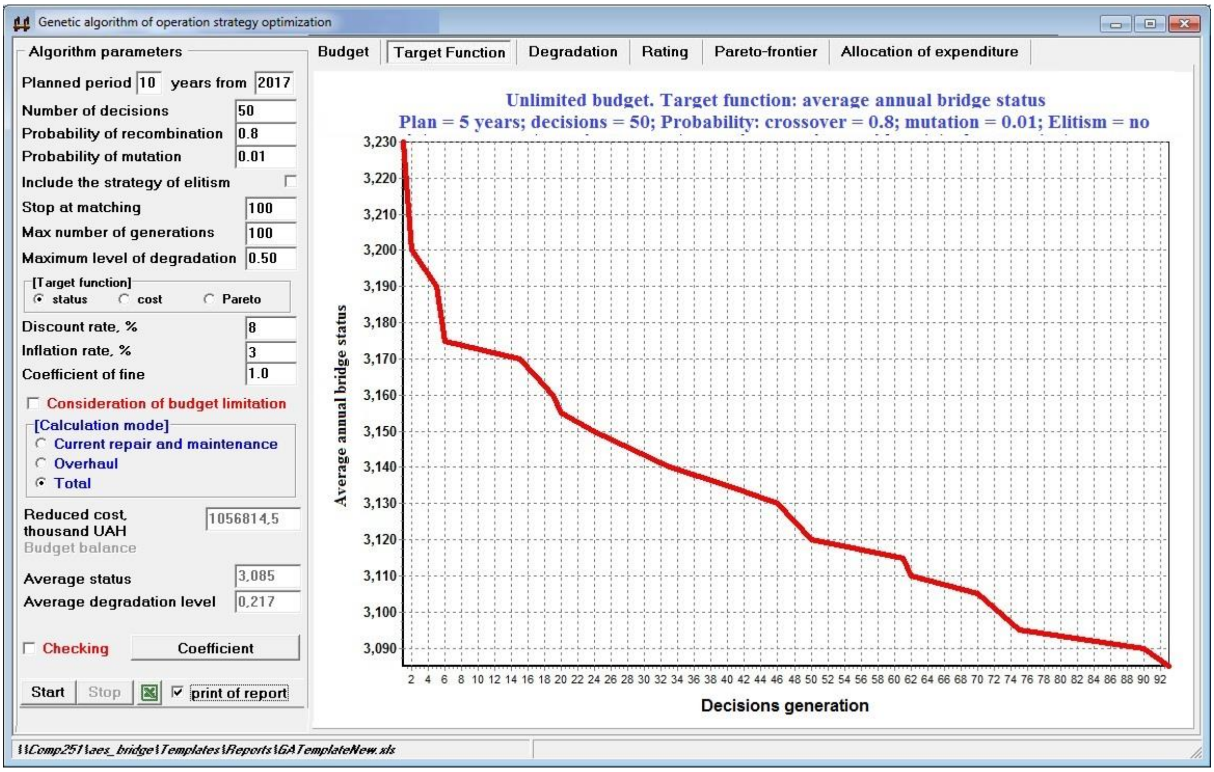

Fig. 4 Optimization window in AEBMS

Table 4. The program fragment of the work for each bridge for a given period with a given strategy

Year	States at the beginning of the year	Degradation level at the beginning of the year	Work types	States at the end of the year	Degradation level at the end of the year	Estimated cost of works (thousand UAN)
		Sumy region, highway M-02				
			Bridge on km 150+619, Age - 6 years, Area = 744,7			
2017	2	0,170	current minor repair	2	0,145	2848,5
2018	2	0,145	current minor repair	2	0,120	2848,5
2019	2	0,120	current minor repair	2	0,095	2848,5
2020	2	0,095	current minor repair	2	0,070	2848,5
2021	2	0,070	current minor repair	1	0,050	2848,5
			Bridge on km 161+450, Age - 12 years, Area = 320,6			
2017	3	0,331	maintenance	3	0,371	64,1
2018	3	0,371	maintenance	4	0,411	64,1
2019	4	0,411	overhaul	1	0,050	3430,4
2020	1	0,050	maintenance	2	0,056	32,1
2021	2	0,056	current minor repair	1	0,050	1226,3
			Bridge on km 178 +232, age - 12 years, Area = 836,2			
2017	3	0,377	maintenance	4	0,417	167,2
2018	4	0,417	overhaul	1	0,050	8947,8
2019	1	0,050	maintenance	2	0,056	83,6
2020	2	0,056	current minor repair	1	0,050	3198,6
2021	1	0,050	current minor repair	1	0,050	10662,2
					Total	42118,9

Fig. 5 The graph of changes of the averaged average weighted degradation by the years

5. Conclusions

The effectiveness of the application of genetic algorithms in the models of life cycle optimization of road bridges elements is proved by this study.

The developed GA procedure and the methodology of its application are unique. It implements the search of a global optimum in the complex task of the exploitation system by the model of the bridge's elements degradation in the function of time and by the model of the cost of repair and restoration measures.

The developed GA is different from the classic one in as it takes into account the features of the allowable sequence of implementation of various work types of bridge repair which depends on the structure's degradation level and the works that have already been assigned during the previous steps (in past years).

Additionally, it should be emphasized that the developed model of the life cycle of road bridge's elements and its program implementation by the GA method is of a network level and it optimizes the performance of repair works within a certain road network and a certain region.

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