

I -27 MULTI-OBJECTIVE OPTIMIZATION MANAGEMENT OF STEEL BRIDGES

INCORPORATING THEIR COATING SYSTEMS

Chunlu Liu¹ and Yoshito Itoh²

[Abstract] Due to the large stock of steel bridges, the painting cost of their coating systems takes a high portion of the annual maintenance budget. The painting cost for maintaining a steel bridge is higher than the cost for the structural repair, the pavement maintenance, and other performance considering the whole lifecycle of bridges. Furthermore, the condition of the coating system has a great effect on the condition of the structural component under it in addition to the aesthetic perception of bridges. Therefore, it challenges the bridge engineers to search an economic and efficient painting planning for determining the appropriate optimal time to apply a coating maintenance method for each steel bridge. This research proposes a multiobjective optimization strategy to deal with the tradeoff between the painting cost and the structural safety for the steel bridge superstructure using a modified genetic algorithm. A numerical example is illustrated for steel bridges located in Nagoya City.

[Keywords] Coating System, Genetic Algorithm, Hybrid Optimization, Maintenance Management, Multiobjective Optimization

1. INTRODUCTION

According to the statistical yearbooks on the highways in Japan, the number of bridges over 15 m in their length reached 125,000 on April 1, 1998^[1]. The total length of these bridges is about 7200 km. Among these bridges, steel bridges are 40.8% and 49.8% in the number and length, respectively. Furthermore, the length of 254 steel bridges in Nagoya City is about 81.6% of the whole length of 435 bridges located in the city. Figure 1 shows the percentages of steel bridges in both Japan and Nagoya City by means of the number and length percentages. Therefore, the steel bridge management occupies an important place in maintaining the national or regional bridges open for constant use, and the performances of

steel bridges attract the great attention of bridge engineers. The service life of a steel bridge is affected by several factors such as the fatigue, loading capacity, and corrosion that are induced from the natural performances or human activities. Necessary strategies have to be carried out to protect the bridges against these negative influences such as the coating system of a steel bridge superstructure.

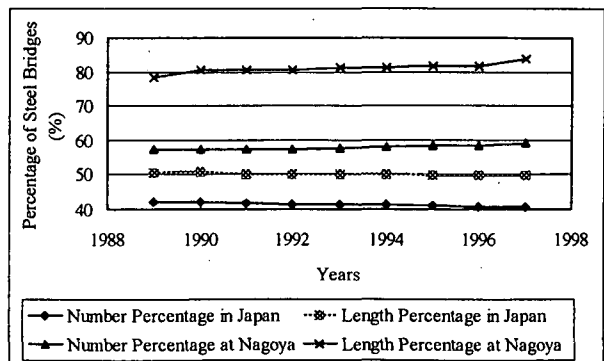


Figure 1: Percentages of Steel Bridges

¹ Assistant Professor, Department of Civil Engineering, Nagoya University, 464-8603

² Professor, Center for Integrated Research in Science and Engineering, Nagoya University, 464-8603

Corrosion of steel bridges has been an endless and costly bridge maintenance problem, and it is one major deterioration cause of steel bridges. Numerous failures of steel bridges due to corrosion and related phenomena have been reported in a lot of literature^[2, 3]. For most steel bridges, a paint coating system is required to provide corrosion protection and to enhance the aesthetic appearance. The painting cost for the steel bridge maintenance over the design life is very high, which is only less than the initial construction cost and higher than the cost for the structural repair, pavement maintenance, and so on^[4]. On the other hand, about 20% of the annual maintenance budget is used for the painting, and only 14% and 8% are allocated for the structural repair and pavement maintenance respectively in Hanshin Expressway Public Corporation^[5]. Furthermore, the environmental and health concerns about the removal and disposal of lead-based paints increase costs related to the painting of steel bridges. On the other hand, the repair cost and structural safety of the steel bridges should be considered simultaneously while a decision is made for the coating systems. This issue can be formulated as a multiobjective optimization problem including the minimum for the coating system cost and the maximum for the structural safety criterion.

This research aims to develop an optimization method to find the ideal cost and safety tradeoff by modifying the conventional genetic algorithm (GA). Efforts have been undergone for several years to apply genetic algorithms for multiobjective optimization issues in the field of infrastructure management^[6-9]. However, the procedure is some limited due to the disadvantages of GAs as mentioned in the next section. In this paper, a new GA optimization procedure is proposed to overcome these disadvantages with several

modifications including the local search, elitist strategy and adaptation of basic operators. Numerical analyses are carried out using the steel bridges located in Nagoya City to investigate the possibility to apply this optimization procedure for the infrastructure management.

2. DESCRIPTIONS OF GAS

In most books or papers on GAs, only the advantages of GAs were discussed. As a computing method, GAs also have some disadvantages^[10]. In the remaining of this section, some disadvantages will be discussed and the potential solutions will be proposed.

It is well known that GA is a robust method in finding the global near-optimum solution. However, once the optimum solution region is identified using GA, finding the true optimum becomes inefficient or impossible. Therefore, GA is always called a near-optimum search method. This problem comes from the discrete coding representation and the random nature in the GA procedure. Integrating GA and the local search approach such as the simulated annealing may be an efficient approach to find the exactly optimal solution or solutions. The previous research suggested a method in which a single bit value is simply changed from 0 to 1 or 1 to 0^[11]. If the fitness of the modified string is better, the original string is replaced using a modified string. Otherwise the original string remains. This test is executed repeatedly from the first bit to the last bit of a coded string.

In the GA optimization procedure, there exist some duplicated strings in one generation and between two generations. For example, some eliminated strings in previous generations may be revived after the crossover or mutation operator, and some near-optimal solutions may

survive in several subsequent generations. These duplicated strings increase the useless calculation time and slow down the optimization process. The elitist strategy guarantees the survival of the best individual in a generation. This strategy ensures the continuous increase of fitness values generation after generation. This strategy can be implemented by replacing the worst individual in the next generation by the best individual from the previous generation for the purpose of the stable increase of the best and average fitness values. A parameter named *generation gap* G ($0 < G \leq 1$) was defined to permit overlapping populations in the previous research. Giving the population size is represented as n , nG individuals of each generation will be generated by reproducing the selected individuals in the previous generation, and $n(1-G)$ will be copied directly from the best solutions in the previous generation.

GA is relatively weak in dealing with the constraint conditions within the optimization process. The popular way is to transform the constraints into a penalty function that is a part of the objective function or to eliminate the solutions that do not satisfy the constraints after decoding all strings. Either way wastes a lot of calculation time due to handling the inefficient solutions. It may be better to increase the penalty parameters gradually generation after generation. This idea stems from the fact that with the increase of the generation number more individuals should satisfy the constraints or the distance between the constraint and the solution should be reduced. Furthermore, the fixed GA parameter such as fixed population sizes, crossover probability and mutation probability, are usually defined at the beginning of each run and adopted until the final generation. This causes the calculation speed to be same from the first generation to the final

generation. It may be better that the optimization process is accelerated with the increase of the generation number by changing some parameters. All these approaches are related to the adaptation of GA operators with a generation.

3. FORMULATIONS OF PROBLEMS

The usual coating maintenance methods can be summarized as spot repair, overcoating, and complete recoating^[12, 13]. In spot repair, only rusted or delaminated areas are removed from the surface and a new coating is applied. Areas with minor defects will not be removed until they deteriorate to a specific condition. In overcoating, all defective areas are removed and the entire steel structure is finished with a new coating that is compatible with existing system. The third strategy, complete recoating, was the method used in the past to maintain bridges. In this method, the coating system is allowed to deteriorate until structural damage due to corrosion is so imminent that a new coating system has to be applied. Each of them requires a different operation procedure and provides different effect on the recovery of deteriorated coating system and protection to the steel bridge structures.

3.1 Objective Functions

In this research, two objective functions are formulated for the deterioration condition of steel bridge superstructures and the painting cost of coating systems, respectively. The deterioration condition of coating systems is considered into the deterioration condition (corrosion condition) of steel structures; and the painting cost is the only maintenance cost without consideration of the repair cost of

structural materials.

Figure 2 shows the conceptual graph of multiobjective optimization in which the objective functions are to minimize the cost and deterioration condition. The black points represent a feasible solution set and its Pareto optimal set is stringed by the line. Under the limitation of maintenance budget, the solution with a lower deterioration condition can be found. On the other hand, the multiobjective optimization approach can provide the needed maintenance budget for any given criterion of the deterioration condition.

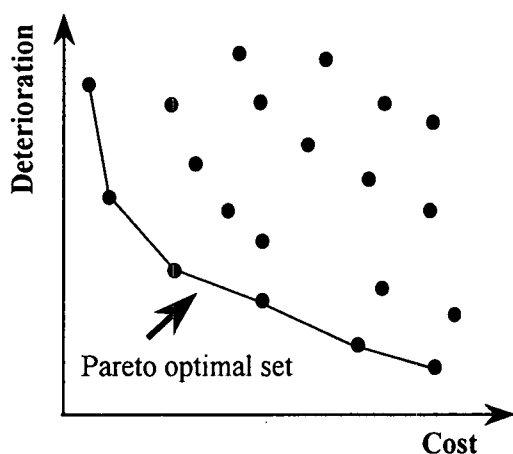


Figure 2: Conceptual Graph of Multiobjective Optimization

The corrosion conditions of bridge structures are represented by the corrosion depth, which can be defined as a function of two parameters, namely the time (ages of structures) (t) and the deteriorated condition of coating systems (1, 2, 3, or 4) (k) based on the previous research^[14]. The deterioration condition of steel structures by means of the corrosion decrements X_c in micron (μm) is expressed as a combined function in the following:

$$X_c = \alpha(k) \times t^{\beta(k)} \quad (1)$$

where the variable k can be one of four values: 1, 2, 3, and 4 to represent the condition of the painting system. The symbol t is the age of the

steel component. Two variables $\alpha(k)$ and $\beta(k)$ are determined according to the following polynomial equations, respectively:

$$\alpha(k) = a_1 + a_2 \times k + a_3 \times k^2 + a_4 \times k^3 \quad (2)$$

and

$$\beta(k) = b_1 + b_2 \times k + b_3 \times k^2 \quad (3)$$

The averages of coefficients a_i and b_i of the functions $\alpha(k)$ and $\beta(k)$ are summarized according to the corrosion decrease of measurements and used to represent the corrosion procedure of steel structures. The regression values of coefficients a_1 , a_2 , a_3 , and a_4 are taken as 102.75, -85.71, 42.67 and -5.27 respectively, and the regression values of b_1 , b_2 , and b_3 are -0.02414, 0.31881, and -0.03795 respectively^[14]. Figure 3 shows the corrosion depth curve with time while the coating system is in different deterioration conditions using these regression values.

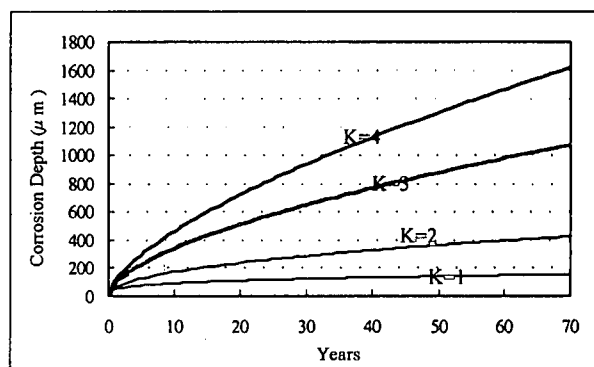


Figure 3: Prediction of Corrosion Depth

The painting cost $C(i)$ of a steel bridge i for a given period T is formulated in the following according to the discount rate r , the unit cost $c(m)$ of painting method m , and the surface area $s(i)$ of the superstructure of the bridge i ,

$$C(i) = \sum_{t=1}^T ((1+r)^{-t} \times c(m) \times s(i)) \quad (4)$$

where m can be selected from the three popular painting methods including spot repair,

overcoating, and complete recoating. For the purpose of calculation simplicity, only the painting planning of steel I-girders is taken into consideration, and the surface area of a girder is obtained by multiplying the girder length and its extended width that is sum of two heights of the web and three widths of the flange.

The optimization objectives in this research are to minimize the two objective functions given in Eqs. (1) and (4) simultaneously. In the conventional optimization approach, the most popular way is to transfer one of these objective function as the constraint or to formulate a new hypothetical function by combining these two objectives. Then, the problem will be solved using a single objective optimization method. The main obstacle of these ways is that the final results are highly sensitive to the initial artificial input data to represent the relationship between two objective functions.

3.2 Painting Strategies of Coating System for Steel Superstructures

Each usual coating maintenance method requires a different operation procedure and provides a different effect on the recovery of deteriorated coating system and protection to the steel bridge superstructures. The long-term maintenance cost of the coating systems is conflicting with the structural safety of steel structures. Table 1 shows the probabilistic selection strategies of painting methods according to the coating system condition. However, to a specific bridge at a given year, it is decided randomly. It is noted that the painting cost consists of several parts and varies with the condition such as the traffic condition, the height of the painting position, the pattern of the surface of the structure, the structural components (web or flange), and the

quality requirement, and so on. However, in this research the unit costs of spot repair, overcoating, and complete recoating are assumed constant as 10000, 20000, and 30000 Yen/m² respectively^[13].

Table 1: Selection of Painting Strategies

| Painting Strategy | Coating System Condition | | | |
|-------------------|--------------------------|-----|-----|-----|
| | 1 | 2 | 3 | 4 |
| No painting | 50% | 25% | 0 | 0 |
| Spot repair | 50% | 50% | 25% | 0 |
| Overcoating | 0 | 25% | 50% | 50% |
| Recoating | 0 | 0 | 25% | 50% |

In addition, due to the lack of the data, the condition of the coating system of a bridge girder is determined according to the age of its coating system. The average service life of the coating system is assumed to be 12 years. The condition is designated to 1 or 4 if the age of a coating system is less 3 years old or elder (and equal to) than 9 years old. If a coating system is equal to or elder than 3 years old and less than 6 years old, its condition is assigned to be 2. The condition 3 represents that the coating system is equal to or elder than 6 years old and less than 9 years old. The effect of painting activities is determined by revising the condition of the coating system. No direct function is performed to the structure from the painting activities. It is assumed that the painting activities of spot repair, overcoating, and complete recoating can reduce the age of the coating system 3, 6, and 9 years at most, respectively.

4. NUMERICAL EXAMPLES

4.1 Description of Case Study

For the purpose of examining the proposed multiobjective optimization approach discussed

above, a small example with six bridges in Nagoya City is prepared. The data of these bridges are obtained from the Bridge Inspection Database of Nagoya City as shown in Table 2. These data represent the basic parameters of six bridges in the inspection year of 1992.

Table 2: Basic Data of Bridges

| | Bridge Number | | | | | |
|-------------|---------------|------|------|------|------|------|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| <i>L</i> | 39.3 | 27.8 | 18.4 | 87.4 | 27.2 | 27.0 |
| <i>W</i> | 24.7 | 8.50 | 7.0 | 27.0 | 7.0 | 13.0 |
| <i>Y</i> | 57 | 61 | 68 | 71 | 79 | 82 |
| <i>k</i> | 1 | 1 | 2 | 2 | 3 | 3 |
| $\alpha(k)$ | 54.4 | 54.4 | 59.8 | 59.8 | 87.3 | 87.3 |
| $\beta(k)$ | 0.26 | 0.26 | 0.46 | 0.46 | 0.59 | 0.59 |

In Table 2, the symbols *L*, *W*, and *Y* represent the bridge length, the extended width as mentioned above, and the constructed year of a bridge respectively, and the symbol *k* is the deterioration level of the coating system. The construction year is used to determine the age of the bridge girder and the condition of the coating system *k* is calculated according to the age of the coating system. The two parameters $\alpha(k)$ and $\beta(k)$ are calculated using the regression values given above in this paper. In addition, the discount rate is assumed to be 1.75% per year during the planning period.

4.2 Multiobjective Optimization Procedure

Figure 4 illustrates the multiobjective genetic algorithm implemented in the present study^[7]. The program starts from the initial generation. After comparing the objective functions of all individuals, the initial Pareto optimal set is generated. For each generation, the multiobjective optimization procedure first determines the fitness functions of individuals in the previous generation using two techniques,

Pareto optimal ranking and fitness sharing. Then, two strings at the present generation are selected on the basis of their fitness, and reproduced as two individuals of the next generation by crossover and mutation until the whole population is recreated. Finally, the multiobjective optimization genetic algorithm decodes and evaluates the strings of this new generation, and revises the Pareto optimal set. This procedure is repeated many times until one of the following termination criteria is satisfied: (1) the maximum generation number is reached; and (2) the convergence index is sufficiently small.

In this research, the painting actions are used directly to code the GA strings. In Figure 4, the string bits 1, 2, 3 and 4 represent cleaning, spot repair, overcoating and recoating, respectively. The string of a painting plan consists of many sub-strings representing the painting strategies of bridges in a given order. The string length is the sum of all sub-strings' lengths. In a sub-string, every string bit from left to right represents the painting action at one year from the beginning to the end of the plan period^[7].

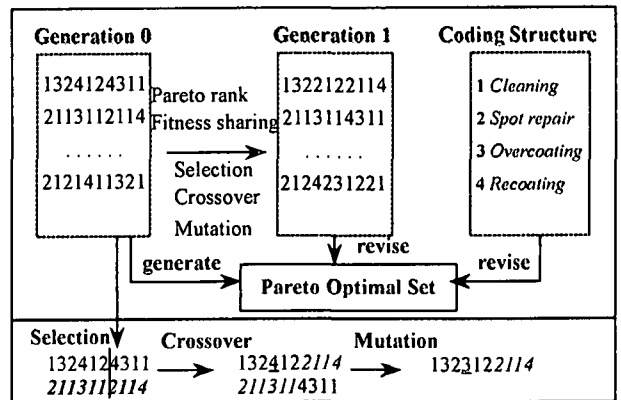


Figure 4: Optimization Process

4.3 Analysis of Calculation Results

The above analysis procedure has been programmed in FORTRAN on a workstation. Figure 5 shows the calculation results of

population distributions at several generations. The symbols \diamond , \square , \triangle , and \times represent the individuals of populations 0, 10, 50, and 100, respectively. It is clear that the solutions are improved with increase of the generation number because the population distributions move to both less painting cost and corrosion depth that are the optimization targets. It is also noticed that the evolution speed decreases with the increase of generation number, which reflects the convergence of the proposed optimization method.

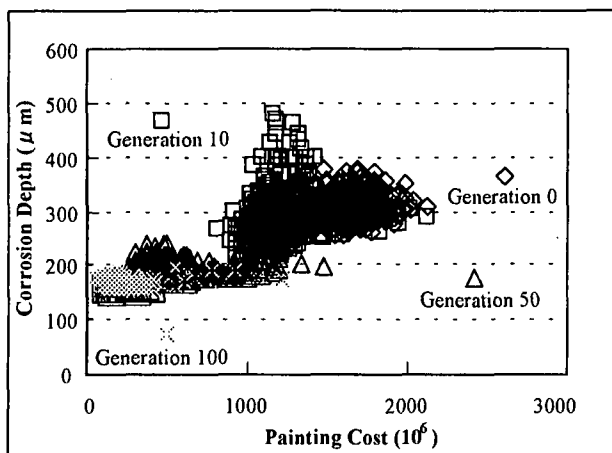


Figure 5: Distribution of Populations

In this analysis, the planning period is 10 years. The population size, crossover rate, mutation rate are 200, 80% and 1% respectively. The number of class used to divide the solution candidates into several groups is assumed to be 5. These parameters are found to be appropriate by various trials of runs. The units for painting cost and corrosion depth are Yen and micron, respectively.

Figure 6 shows how the Pareto optimal sets evolve to the left and down with the increase of generation number from generation 0, through generations 10 and 50, to generation 100. The Pareto optimal set at the generation 100 shows the trade off between the painting cost and corrosion depth. This trade-off shows the possible painting plans. The decision-maker

can select one ideal painting planning corresponding to the final Pareto optimal set according to the further particular requirements.

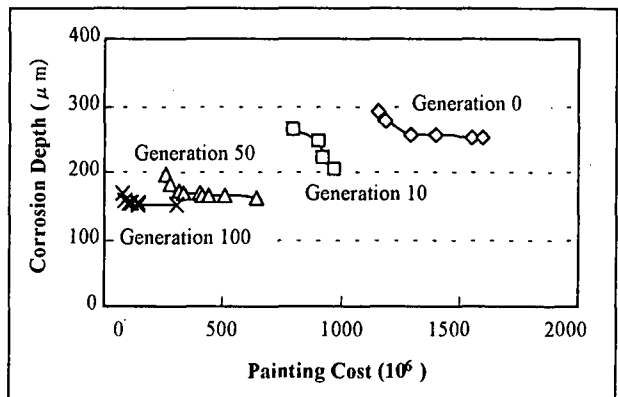


Figure 6: Pareto Optimal Sets

In contrast with single objective optimization problems, there may not exist a single solution that is optimal with respect to all objectives of a multiobjective optimization problem. Instead, there are a set of solutions which are superior to the rest of the solutions in the search space considering all objectives, and no solution in this set is absolutely better than the other solutions. In other words, the improvement of any single objective in one solution of a Pareto optimal set will result in a negative impact on at least one other objective. The purpose of multiobjective optimization is to find this so-called Pareto optimal set of solutions, not a specific solution.

5. DISCUSSION AND CONCLUSIONS

Although there exist a number of classical multiobjective optimization techniques, they are difficult to be applied to deal with the real-world practical problems because the detailed problem information is required. Since genetic algorithms use a population of points, they are able to find the multiple Pareto optimal

solutions simultaneously. In this research, the corrosion degree of steel bridge superstructures is first formulated according to their ages and the deterioration condition of the coating system. Then, the cost for maintaining the coating systems is formulated for a long period. A multiobjective optimization strategy is proposed to deal with the cost and safety tradeoff for the painting planning of the coating system using a modified genetic algorithm. Finally, a numerical example is illustrated for steel bridges located in Nagoya City.

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