Deliverable D3
Review of existing procedures for Optimisation

Status (P)

BRIME
PL97-2220

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Date: January 2001

PROJECT FUNDED BY THE EUROPEAN COMMISSION UNDER THE TRANSPORT RTD. PROGRAM OF THE 4th FRAMEWORK PROGRAM

Review of Existing Procedures for Optimisation

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CONTENTS

EXECUTIVE SUMMARY

SCOPE

Europe has a large capital investment in the road network including bridges, which are the most vulnerable element. As bridges age, deterioration caused by heavy traffic and an aggressive environment becomes increasingly significant resulting in a higher frequency of repairs and possibly a reduced load carrying capacity.

The purpose of this project is to develop a framework for the management of bridges on the European road network that enables bridges to be maintained at minimum overall cost i.e. taking all factors into account including condition of the structure, load carrying capacity, rate of deterioration, effect on traffic, life of the repair and the residual life of the structure.

SUMMARY

This report gives an overview of procedures used in some European countries and in the United States for optimisation of maintenance strategies. It is the first of two reports which are going to be delivered by WP 6 -"Priority ranking and prioritisation". The main objective of this work package is to derive general guidelines and/or recommendations for prioritisation.

The first chapter of the report discusses the role of optimisation of maintenance strategies of existing bridge structures in a Bridge Management System (BMS). Prior to the seventies the emphasis was put mainly on new structures, with little or no attention being given to the condition and performance of older structures. Due to deterioration, increasing loads and lack of funds for maintenance, management of bridge structures with the aim of preserving an acceptable level of performance, has become increasingly difficult. Therefore, different procedures have been developed to help optimise the maintenance of bridge structures within the limited available funds.

In Chapter 2 the objectives for optimisation of the maintenance of bridge structures are given. One of the most important objectives is when and how to allocate the available funds for maintenance work to preserve bridge structures at an acceptable level of service for the lowest cost. Another objectives is to analyse different repair strategies for each structure (project level optimisation) and to select the optimal one, and to determine what savings can be achieved through different maintenance strategies.

In Chapter 3 an overview of optimisation procedures used in some European countries (Denmark, France, Norway, United Kingdom) and in the United States is presented. The overview for each country includes the main characteristic of existing optimisation procedures and in some cases future trends in improvements of optimisation procedures.

Chapter 4 contains a general review of mathematical methods used for optimisation. The methods are divided into Standard mathematical formulation and Artificial Intelligence methods, such as Neural Networks and Genetic Algorithms. A short review of some papers

dealing with optimisation of structures is also presented. These papers include some which deal with cost optimisation of structures.

In the last two chapters recommendations and conclusions for further work are made aimed at the improvement of existing data and the addition of new data for BMS, and which are very important for the optimisation process.

IMPLEMENTATION

This review of optimisation procedures is the basis for the discussion and further work within Workpackage 6. It should also stimulate further improvements of existing optimisation procedures and/or development of new ones. The review has shown that different mathematical tools can be applied in the optimisation analysis of maintenance options. Some results of this review can also be used in the Workpackage 6 "Prioritisation" and in the Workpackage 7 "Systems for bridge management".

REVIEW OF EXISTING PROCEDURES FOR OPTIMISATION

ABSTRACT

Bridge structures are a very vulnerable part of the road network due to deterioration processes and increasing loads. In the past attention has been given new structures, but little or no attention has been paid to the condition and performance of older structures. Due to deterioration, increasing number of bridge structures and lack of funds for maintenance, the management of bridge structures with the aim of preserving an acceptable level of performance has becoming increasingly difficult. Therefore, different procedures have been developed to help optimise maintenance of bridge structures within the limited funds available. Some of these procedures are based only on engineering judgement, some are completely computerised and some are based on a combination of engineering judgement and computers, which manipulate data stored in the BMS for the specific purpose of optimisation.

The aim of the optimisation is to get the best maintenance option at minimum cost. Different mathematical methods have been applied to solve the problem of minimising costs. In recent years new methods of artificial intelligence, for example Neural Networks and Genetic Algorithms, have been introduced to solve the problem of minimising costs for different maintenance strategies. The methods themselves are only as good as the input values for costs, modelling and other random variables. Therefore, for each type of defect, it is necessary to know the whole life cost for each maintenance option. An important part of the optimisation process is prediction of future deterioration of the structure or its elements. Therefore, different types of periodic inspections with the help of non-destructive techniques of testing are very important for predicting future deterioration. Continued research in these areas is needed as well as systematic collection of data, on which the optimisation process is based.

1.0 INTRODUCTION

In the last few decades in most countries around the world the number of vehicles on the main routes has increased enormously due to the needs of transportation and economic development. The need for quick and efficient transportation of goods and people has encouraged the construction of new and improvements to existing road infrastructure networks. As bridge structures play an important role in the road infrastructure, with the improvements and construction of new road networks has increased the number of bridges substantially.

During the late sixties and early seventies in developed and industrialised countries the condition of existing structures has become increasingly important. Due to deterioration a bridge structure in USA collapsed causing loss of lives and goods as well as disruption to the transportation networks. Before this accident the main focus was on the construction of new structures, with little or no attention being paid to the condition of existing structures.

Due to their position in the infrastructure network, bridges are especially vulnerable to constant and serious deterioration, which is mainly the consequence of:

- environmental loading (marine environment, use of de-icing salt during the winter to provide good traffic conditions, air pollution, temperature, continuous exchange of wet and dry conditions, etc…),
- ageing processes,
- poor planning of maintenance operations,
- lack of funds for regular maintenance,
- underestimation of the role of proper and on-time maintenance in the past,
- poor design, detailing and execution of the structure,
- increased volume of bridge stock,
- increased axial loads on roads.

Due to deterioration processes the condition, load carrying capacity, serviceability and/or expected service life of many bridge structures have become jeopardised. To put deteriorated structures back to their initial state, a vast amount of money would be needed. As such a vast amount of funds are not available in the short nor in the long term such a policy would not be economically wise and justifiable. Therefore a decision must be made in each budget year on the maintenance work to be done on bridge structures within the limits of short and long term available funds to put deteriorated structures back to an acceptable state as well as to preserve the present condition or to slow down the deterioration of the younger structures.

Aware of the rising problems associated with the available funds for preservation of the functionality, safety, load carrying capacity and satisfactory condition of bridge structures, Road Authorities in many countries in Europe and United States have implemented various types of database. The main purpose of these databases has been helping Road Authorities in decisions making regarding the activities that have to be undertaken to preserve or improve the condition of the bridge stock in the current budget year or in a definite period of time. These databases usually provide data about bridge inventory and condition of bridges. In earlier times these data were stored on coded sheets and as such were impractical for implementation. With development of computers, and especially PCs, databases have become larger and can store a vast amount of data, which can be manipulated in different ways and for different purposes. The possibility of manipulation for specific purposes of all kind of data related to bridge structures is a basis for development of a Bridge Management System (BMS). Each BMS may be composed of several modules, which can be exploited on the basis of demands and wishes of users and their technical capabilities, for updating already acquired data and for storing additional and new data.

An important part of a BMS is the optimisation module. Several optimisation procedures have been developed in the last few decades. The existing ones are constantly improving and new ones are being developed on the basis of past experience and present and future needs.

The development of maintenance optimisation software is assisted by the development of high-speed microcomputers as well as PCs and new mathematical methods such as neural networks and genetic algorithms.

2.0 OBJECTIVES OF OPTIMISATION PROCEDURE

Optimisation procedure has several objectives, of which one of the most important is when and how to allocate the available funds for the maintenance work to preserve the bridge structures of the bridge stock at acceptable level of service for the lowest costs. Optimisation is carried out for the selected time cycle, which can vary from a few years to the whole lifetime of the structure. Another objective of optimisation is to analyse different repair strategies for each structure (project level optimisation) and to select the optimal one. When the optimisation is carried out on the whole bridge stock (network level optimisation), in some cases the selected optimal maintenance strategy on the network level may not be the same as for the project level optimisation. One objective of the optimisation is also to find out when savings can be achieved through different maintenance strategies. Optimisation of maintenance strategies is carried out taking into account constraints, which in great deal influence the final decision of the maintenance policy. The number of the constraints varies from the procedure to procedure, but there are some of them, which are the most important and are incorporated in most of the optimisation procedures. These constraints are available funds, the acceptable levels of structure's condition, load carrying capacity, serviceability and remaining service life.

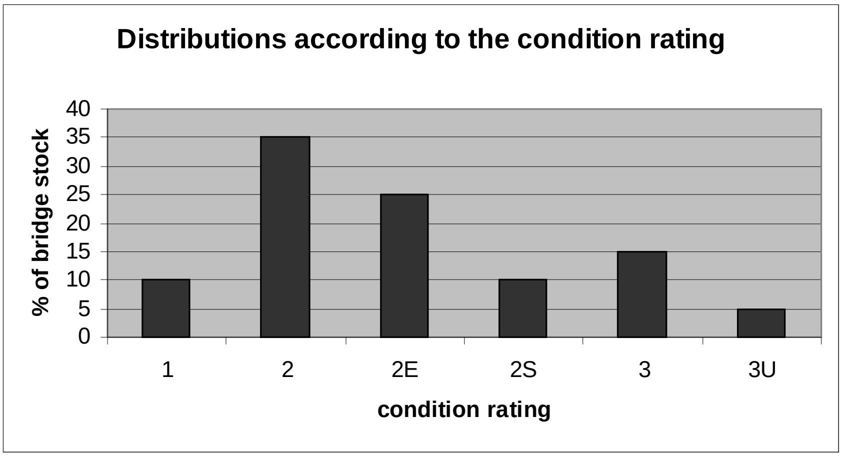

Fig.1: Classification with respect to the condition rating classes

The first step before optimisation procedure can be applied is to gather information of the condition of individual bridge structures (project level optimisation) and the bridge stock as a whole (network level optimisation). The information is collected by carrying out periodic inspections. In most of the countries, which carry out the periodic inspections, the condition assessment of the structures is made by the adopted procedure. Some of them are briefly described in deliverable D2 of the Brime project[1]. After evaluation of condition assessment of the bridge stock is carried out, the bridges are classified according to their condition rating into different categories. These categories are structured with respect to the assessed severity of condition of the bridge component and urgency of the intervention. The classification can be made in descending order with respect to the total condition rating being the highest the worst condition state and the urgency of repair for those bridges, which exhibit satisfactory condition rating, but some urgent actions must be carried out (as an example, to provide satisfactory traffic safety conditions). The procedure, which classifies the bridges within the bridge stock with respect to their condition assessment, is called prioritisation. Two typical approaches to prioritisation are shown on figures 1 and 2.

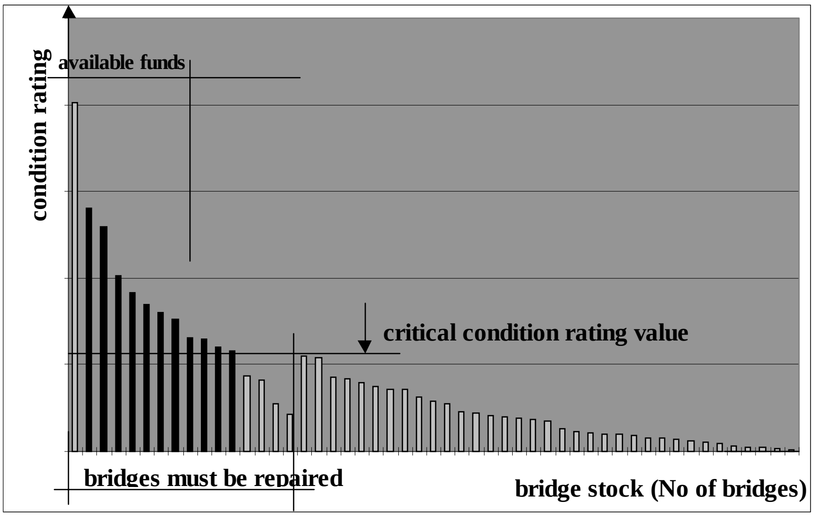

Fig.2: Classification according the total condition rating and urgency of repair

After the candidate bridges are selected by any method, the optimisation procedure is firstly applied on the project level and then on the network level.

When evaluation of optimised maintenance strategies on short and long term are carried out, the constraints of allowable funds and value of money must be taken into account as well as the minimum allowable level of structural condition, load carrying capacity, users safety and traffic safety. The total costs should be taken into account, i.e. direct and indirect costs. In assessment of traffic delay costs, which are part of the indirect costs, the care of presenting them should be taking into account. It is recommended to record them separately from the other costs, because in certain cases on busy roads these costs can be substantial and can overshadow the real engineering costs[10].

3.0 REVIEW OF OPTIMISATION PROCEDURES

Kamal an Hojjat[2] made a review of papers on cost optimisation of concrete structures. From the review of papers that have been published on optimisation of structures, a great majority of papers are concerned with minimisation of the weight of the structure, and only a small fraction of them deal with cost optimisation of structures. From the review of the papers they made they found only two, which deal on cost optimisation of realistic three-dimensional structures. As such, there is a need to perform research on cost optimisation of realistic three-dimensional structures, especially large structures with hundreds of elements where optimisation of costs can result in substantial savings. The great majority of papers on cost optimisation of concrete structures include the material costs of concrete, steel and formwork only. Some researches ignore the cost of the formwork. They concluded that this cost is significant in industrialised countries and should not be ignored. Other costs such as the cost of labour, fabrication, placement, and transportation are often ignored. They emphasised that additional research needs to be done on life-cycle cost optimisation of structures where the life-cycle cost of the structure over its lifetime is minimised instead of its initial cost of construction only. At the end of their final comments they stated that the researches of reliability-based optimisation make a valid argument about the inclusion of uncertainties in loads and resistance in the optimisation process. At the end they concluded that at present, the probabilities of failure and the expected failure costs cannot be calculated with any measure of certainty due to insufficient statistical data, therefore they have to be chosen somehow arbitrarily.

In the following paragraphs a short review is made of optimisation procedures, which are currently used in four European countries and the USA. A review is made on the basis of the available publications, proceedings and other official documents, and from personal contributions of some participants in the BRIME project. The aim of this review is to provide an insight into the existing procedures, their common features and significant differences. In the most of the available literature only a description of the optimisation procedures is given. The mathematical expressions were found only for the prioritisation procedure adopted in Pennsylvania[19].

3.1 Denmark[3,4]

As elsewhere throughout the world the allocated funds for bridge maintenance in Denmark are not sufficient for carrying out all the proposed repair and maintenance work. Therefore some priority of bridges, which will undergo a repair or extensive maintenance work in a definite period of time must be made. The priority ranking should be done in two phases. First phase includes an automatic (preliminary) ranking and the second phase includes a manual (final) ranking. The reason why the ranking has to be done in two phases is because a large portion of data is not available at the site during inspection and because other relevant information influencing the priority ranking must be taken into account.

One of the main purposes of Bridge Management System in Denmark is to ensure the safety and serviceability of the bridges in the most economic way for a longer period of time.

Therefore the economic analysis of proposed repair work, which is based on the data obtained from the special inspections, are taken as the basis for the optimisation. The outcome of this procedure is that it is not necessarily the bridges that are most severely damaged get highest priority for the repair work. This is a result of taking into consideration the consequences of the extra costs in the case of not allocating sufficient funds. These extra costs are additional direct costs caused by a larger amount of repair work, if repair work is postponed, and user costs in the case of temporarily closed bridge or an applied weight restriction.

Optimisation procedure of proposed repair work for bridges in a bridge stock is made for a five-year period. The data for the optimisation procedure or input data for the optimisation module in DANBRO database system are budgets for the coming five year period, data from the economic evaluations of the data of special inspections and discount rates. The program finds through an iterative process the set of strategies, one for each bridge, for which two criteria are met: the extra costs are the lowest possible and the total estimated costs lie within the budget for each of the five years. After the automatic optimisation is done, the result is carefully studied. The choice of strategies may be altered manually taking into account factors, which can not be directly expressed in terms of money (co-ordination with other works on the same road, environmental aspects, etc…).

In addition to the five-year budgets there is a need for long term estimates for bridge rehabilitation. Therefore for each bridge the year of construction and the type and dimensions of all standard bridge components are registered. For standard bridge components average repair intervals and corresponding average repair costs as well as average service lives and replacement costs are also registered. Based on these data the total future budgets are calculated. Although the uncertainty is relatively large, the accuracy is considered sufficient for indicating the trend of the costs.

For economic evaluations of data of special inspection (proposed repair work) cost estimates for proposed repair works are needed. Therefore a Book for standard repair works and Price Catalogue were developed. They are used for preparing the Bill of Quantities for a specific project. After the tendering, the unit prices from the two lowest bids are entered in the database. In this way cost estimates are always updated and available for the standard repairs and thus for the five-year budgets derived from the principal inspection.

3.2 France[5,6]

Optimising the resources which are allocated to preserving bridges on the national network in order to guarantee that the conditions for road users are satisfactory is of prime economic importance. In response to the problem of assessing and optimising the resources allocated to maintaining the bridges, Directorate of Roads and Highways launched in 1994 a campaign to assess the bridges on its non-conceded roads. Therefore it was introduced the IQOA indicator, which is briefly described in deliverable D2[1] of Brime project. This indicator describes the overall condition of the bridge stock. It should improve the way routine maintenance schedules cope with the preservation of the bridge stock and allow a more effective budgetary and technical policy to be developed with reference to the quality and durability of structures.

The budget, which the Directorate of Roads and Highways allocates to bridge maintenance, consists of funding for survey and routine maintenance and funding for major repairs.

Funding for survey and routine maintenance consists of fixed annual sums, which are allocated to each Public Works District Direction on the basis of the surface area of bridges on the national network for which they are responsible. It should be noted that this maintenance funding for bridges is not separate, being merely part of the overall allocation (roads and bridges) which each Public Works District Direction receives for maintenance of the national road network.

Allocation of the funds for major bridge repairs is governed by a specific procedure. The Public Works District Directions propose to include bridge repairs in a so called triennial programme. The Directorate of Roads and Highways decides whether a repair project is to be included in the triennial programme and allocates the necessary funding as the programme and works progress, after it has investigated the requests according to the procedure. The triennial programme is a rolling program so that each year the scheduling of works for the coming year and the pre-scheduling of works for the following two years can be adjusted on the basis of changing priorities.

The main stages in the investigation procedure for the inclusion of works in the triennial programme are as follows:

1. The Public Works District Direction draws up an inclusion file for each bridge involved. This file contains description of the bridge and its deficiencies, diagnosis and envisaged repair works, cost of repair and timetable.

2. This file is sent to the Directorate of Roads and Highways, the General Bridge Inspector and technical organisations such as the Roads and Highways Engineering Centre (SETRA) and the Public Works Regional Engineering Centre (CETE). The General Bridge Inspector sends its technical verdict (drawn up in consultation with the mentioned technical organisations) back to the Directorate of Roads and Highways and finally proposes for each bridge: either acceptance of the file in the case of simple repairs or, if not, production of a more precise and detailed file to be re-submitted to the General Bridge Inspector for approval at a later date.

3. The Directorate of Roads and Highways draws up the triennial programme with reference to General Bridge Inspector verdicts and annual budget availability.

As can be seen from described procedure, the decision on repair work is made only on engineering judgement at the several levels. In France at the moment there is no automatic optimisation procedure used in optimisation the repair work of the bridge stock.

3.3 Norway[7]

National road bridge standards or service conditions must be as nearly as possible similar throughout the country. Maintenance and repair should be carried out in such a way that the quality of the bridges is not decreasing below the acceptable level given by the Public Road Administration Handbook 111 - "Maintenance Standard".

Based on the damage description and the condition assessment, proposals for repairing damage of Degree of Damage levels 2, 3 or 4 shall be prepared from work descriptions/ process codes. Cost estimates are to be prepared for the proposed action, and an indication should be given which year these activities shall/should be performed in so as to ensure that the specified standard is maintained. The method of condition assessment is briefly described in deliverable D2[8] of Brime project.

Funds for national road bridges are allocated primarily from two major sources: investments and maintenance. Investment funds are allocated in renewal (strengthening, reconstruction) and new construction of bridge structures. Maintenance funds are allocated for the inspection, routine and periodic maintenance and repair of bridge structures. The person responsible for bridge management in each county prepares proposals for the management and maintenance budgets, and reports the need for the renewal or reconstruction of existing bridges both in short term (1 year) and the long term (up to 10 years). Renewal and new constructions will be considered as alternatives to maintenance activities when bridges no longer satisfy mobility and safety requirements. When renewal or reconstruction is to be undertaken as an alternative to maintenance, the person responsible for bridge management in each county must follow up such measures especially to ensure that planning and implementation takes place as intended.

Maintenance and repair shall be performed in accordance with the Public Roads Administration's Handbook 111 - "Maintenance Standard", but bridges demanding the use of resources may cause delayed maintenance of other bridges. In such cases priority assessments shall be performed to determine, which other bridges will be least affected by delayed maintenance. Whenever the cost of necessary repair activities following from a major inspection or special inspection exceeds 20% of bridge's replacement value, alternative strategies should be investigated. If funds are unavailable to follow optimal strategy for the individual bridges, prioritising shall be based on which approach will cause the least detrimental economic impact. A revised strategy could also be considered.

At least two different strategies will be investigated depending on what is relevant. In addition to maintenance costs they should also include road user costs and any costs to society if affected by the various strategies. The following strategies may be considered:

1. Temporary action: Minor repair activity carried out during one period to postpone major work or replacement of a bridge.
2. Major action: Extensive repair work during a brief period to significantly extend the remaining service life of the bridge.

3. New element/bridge: No repair undertaken; however, the existing element/bridge is replaced at the end of its service life.

For each strategy different technical solutions may be considered. When maintenance costs exceed 50% of the replacement value, strategy 3 must be considered. Special consideration should also be given to the elements.

The present worth of the selected strategies shall be estimated and these will form the basis for selecting an optimal strategy. Factors that normally do not enter into the cost estimates shall also be included before the final selection of a strategy. Such factors may include: bridge age, remaining service life, load carrying capability, bridge width/road curvature, vertical clearance, traffic safety, mobility, future usage, aesthetics, historic value. If funds are not allocated to carry out the optimal strategy, prioritising between the various bridges will have to be undertaken.

Prioritisation between bridges is carried out manually by the person responsible for bridge management in each county. When the available funds are known, the person responsible for bridge management in each county will prioritise between the bridges that have reached or will reach a condition that is unacceptable the next year (degree of damage 2 or more and repair recommended within the next year).

Prioritisation between bridges is made as follows (the description of codes is given in deliverable D2[(7)]):

Priority 1: Bridges with degree and consequence of damage 4B
Priority 2: Bridges with degree and consequence of damage 4T
Priority 3: Bridges with degree and consequence of damage 3B
Priority 4: Bridges with degree and consequence of damage 3T
Priority 5: Bridges with degree and consequence of damage 3V-4V
Priority 6: Bridges with degree and consequence of damage 3M-4M
Priority 7: Bridges with degree and consequence of damage 2B
Priority 8: Bridges with degree and consequence of damage 2T
Priority 9: Bridges with degree and consequence of damage 2V
Priority 10: Bridges with degree and consequence of damage 2M

In Norway there is no automatic optimisation procedure in computer based management system yet. Also they don’t use any kind of standard procedure of cost-benefit evaluation in connection to each maintenance or repair project.

3.4 United Kingdom[(9,10,11)]

One of the main objectives of a bridge management system in UK as elsewhere in the world is to minimise costs on maintenance work and to maintain the structures in a safe condition. The condition of bridges is evaluated through several types of inspection. The evaluation is made for different structural items. The report of the inspection is made in terms of the extent, severity, work priority and estimated costs.

The priority for proposed maintenance or repair work is assigned by three levels. For high priority the work should be done during the next financial year to ensure the safety of the public or safeguard structural integrity or avoid high cost penalty. For medium priority the work should be done during the next financial year and a postponement carries some cost penalties. The work with low priority should be done within the next two financial years. Estimated costs should be given for each item of work recommended as a rough guide to the cost involved. It should not include traffic management costs and administration fee.

The Highway Agency currently holds information about structures on its national structures database known as NATS. Maintaining Agents use the financial input data of NATS to submit bids for schemes for the maintenance of its structures and for bids for rolling programmes relating to major schemes and for assessment and strengthening programme. At the currently existing system, only one maintenance proposal is put forward for each scheme. Currently used system does not look beyond the bid year in terms of future work profiles and it also does not provide information on the consequences of not funding any part of the bid. To make optimal use of limited funds, which are allocated for maintenance of bridge structures, the maintenance must be based on longer term network strategy-based systems. For this reason a new computer based structure Bid Assessment and Prioritisation System was proposed by Highway Agency, which will in the future replace the current system. The system will combine strategic needs of individual structures, taking into account alternative maintenance, the application of whole life costing principles and the assessment of risk in terms of road user delays for not carrying out the needed repair work.

Each option of maintenance will cover a period of thirty years. It will be prepared by the Engineer, who will be required to consider and submit a number of bid options to undertake the maintenance work. The reason for requiring more than one option is that the best option for a particular scheme may not be the best option when strategic consideration of the whole bridge stock are taken into account. In proposing maintenance options the Engineer will also look at the implications of not doing the work. In such cases the assessment of traffic disruption and estimation of the road users costs would be needed. For each element the bid comprises the incurred cost, the traffic delay cost and the traffic delay costs if the work is not carried out, for each year in which maintenance work is proposed. The cost benefit of combining work should be reflected in the bids through linking. When the Network Managers and Maintaining Agents are satisfied with the works proposed and can be carried out in their works programme, the structures maintenance bid options are submitted to the Highway Agency for assessment.

The first step of prioritisation is made by type of the maintenance work and the order of importance, which are committed, essential and preventative. The type of maintenance work is determined by comparing the current performance level of an element with the level at which the performance of that element becomes unsafe. Maintenance work on the elements below critical level is categorised as essential. If it is above the critical level, it is categorised as preventative. The argument for doing preventative work is that it will cost more later if the work is not done now. The committed maintenance work is continuation of an existing contract. In this case only one maintenance option is necessary. The second step is made by work categories. The order of priority of work categories is determined by the Highways Agency.

In order to obtain best value of money from maintenance work it is essential to compare maintenance options on the basis of whole life costs, which includes not only of immediate costs, but also future costs arising from the chosen maintenance strategy. For example, the future costs will be much higher if only minor repair is carried out instead of a required full rehabilitation of the structure. Using the whole life costing has two associated problems. The first is that all costs have to be discounted to present value. It is therefore essential to have a long term strategy for maintenance work in parallel with the assessment of annual bids on the basis of whole life costs. The use of whole life costing may give the best strategies for individual structures but may not represent the best strategy for the network. The second problem is the assessment of the road users delay costs. These costs are particularly sensitive to the value of traffic flow rate. As maintenance works are carried out at different times, the delay costs will vary depending on the bridge age when then the maintenance works are carried out.

The user delay costs are not of direct relevance to the bridge owner, who funds the maintenance costs. On the other hand, the delay costs may be substantial for a community, where the maintenance works are carried out. For this reason it is better to include user delay costs, but to record them separately form the engineering costs. In United Kingdom the program Quadro(12) is currently used to estimate the user delay costs. It takes into account road user delays costs (value of time), vehicle operating costs and accident costs. Value of time is calculating vehicle speeds and journey times on the without and with work networks using the traffic flows and speed/flow curves. Vehicle speeds and journey times differ between the without and with work networks due to queuing delays on the main route and the reduction in speed of all traffic on the diversion route. A monetary value is attached to these times using different values for vehicles in "work time" and "non-work time". Vehicle operating costs are calculated using the same relationships as in calculation of Value of time, based on average vehicle speed. Accident costs have their own associated costs. In Quadro accidents are related to vehicle kilometres by an accident rate. Accident costs vary with location and type of road. The costs associated with each accident assume that there are particular number of fatal, serious and slight casualties per accident.

A case study of whole life costing of maintenance options have clearly indicated that the preventative maintenance options provide the best value for money. Although the preventative maintenance works are applied at a younger structure and thereafter more frequently than for example replacement of elements, the preventative maintenance options costs less to carry out and cause less traffic disruption. The traffic delay cost is the major component of the whole life cost for most maintenance options except at the lowest traffic flow rates.

3.5 United States[13,14]

United States has a large number of bridge structures, among which a lot of them are structurally deficient and obsolete. Until late 60's efforts were devoted to the construction of new structures and a little attention was given to maintenance, repair and rehabilitation of bridge structures. In that period national standards for bridge inspection and bridge evaluation did not exist. After a tragic collapse of one bridge structure attention was focused on bridge safety. New requirements for safety inspection, maintenance, condition rating and structural evaluation were drafted and enacted. Implementation of new standards revealed also a need for further research in damage evaluation, repair and strengthening guidelines, strength evaluation of existing bridges and assessment of costs for different repair procedures[15,16,17,18].

The data collected through periodic bridge inspections are maintained in the National Bridge Inventory (NBI) database. The NBI data support federal funding programs, such as Highway Bridge Repair and Rehabilitation Program and the Special Bridge Program, which provide discretionary funding. Decisions, for which bridges put in available money for maintenance, repair or rehabilitation, are currently made using priority ranking procedures or rating formulas. The sufficiency rating, which is used for determination of federal funding eligibility, combines the information reflecting the structural adequacy of the bridge and the associated effect on public safety; serviceability of the bridge structure and how essential and important the bridge is to the public. The ratings are determined by means of a point deduction system. In this system a new bridge would receive a rating 100 and failed structure would receive 0. Bridges with ratings 50 or lower are eligible for federal replacement funds, while bridges with ratings between 50 and 80 are eligible for rehabilitation funds.

To help bridge management authorities taking a decisions on repair or rehabilitation of bridge structures with the limited funds available, several bridge management software programs were developed. The most known are Pontis and Bridgit. Pontis was developed through collaboration between Federal Highway Administration and Bridgit was developed through National Cooperative Highway Research Program.

Pontis is used to provide information in support of network-level bridge planning, network-level bridge maintenance planning and project-level bridge planning. It's models, which are incorporated in the system, can be used to optimise bridge funding for maintenance, repair rehabilitation and as well as improvements. User costs and actual costs are taken into account. Actual costs are costs required to preserve or replace a bridge or a portion of it. User costs are costs incurred by the load postings, user detours, clearance limitations and accidents due to poor geometrics or clearances on the bridge.

Pontis optimisation model is focused on finding for each bridge element in each environment the long-term steady-state policy that will minimise maintenance funding requirements while ensuring the elements will not fail. The model incorporates changes in the element condition, the effectiveness of the owner actions and the costs of these actions into a cost/ benefit ratio for each element and determines the most cost-effective long-term actions. To use Pontis system, the element-level inspection must be implemented instead the component-level inspection.

In the element-level inspection bridge elements are defined and rated according the type, severity and extent of deterioration. Momentarily the system is being capable of considering 160 different types of elements ([19]). A condition rating scale between 1 and 5 is used, being 1 the best and 3, 4 and 5 the worst depending on the element. The output from Pontis provide information on:

- condition and funding levels;
- anticipation of deterioration rates of bridge systems;
- costs for various maintenance, improvement and replacement activities;
- present conditions of the system;
- ranking of proposed bridge activity.

Bridgit optimisation software was developed to help in the analysis of minimising life-cycle costs or whole life costing for bridge stock in the network. The life-cycle cost is the sum of three different costs that occur during the life of a bridge structure. These costs are: design and construction costs, traffic disruption and user delay costs and maintenance costs. The aim of using Bridgit life-cycle costs analysis is to minimise investments in bridge building, travel costs, travel time and bridge operational costs. It is also used for making the analysis how much money should be invested in the bridge network in the long-term (e.g. twenty years) and which bridges should receive funding for rehabilitation, repair and preventative maintenance in the short-term (e.g. two, three years).

The optimisation is executed in two stages. In the first stage different life-cycle activities are developed for each bridge in the network or a selected shortlist in order to estimate the present and future costs for different repair strategies. In the second stage, the optimisation analysis is carried out to prioritise needs and select the most cost-effective options, which satisfy the defined constrained or unconstrained budget cases as well as the aimed service levels. After the most cost-effective option is selected for each structure, the results are summarised to determine the level of funding for a certain period of time. In some states the Bridgit's approach to optimal management was found as an excellent decision support tool.

3.5.1 Pennsylvania[20,21]

Several states in United States have developed their own Bridge Management System, which enable a systematic approach to the management of a bridge stock in the case of limited funds for their maintenance. Pennsylvania State developed its system and implemented it in 1987. Four main specific objectives were put in the development of Penn BMS.

The first was that on demand but al least annually a system must yield recommendations with associated cost estimates for activities, required to enable all bridges on public highways and roads to perform in the most cost-effective manner. These activities include various levels of maintenance, various modes of rehabilitation and replacement. The second was that it must predict present and future needs and associated costs to perform the above activities for all bridges in at least two scenarios, including 'minimum acceptable' and 'desirable'. The third was that it must set on demand but at least annually state-wide and regional priorities for each of the fore-mentioned activities and provides a listing of candidate bridges. The fourth specific objective was that it must provide on demand or at least annually a basis for recommending regional distribution of budgeting funds.

To select the candidate bridges for maintenance a simple prioritisation procedure has been developed. It is consisted of four components: activity ranking, activity urgency, bridge criticality and bridge adequacy. The activity ranking takes into account variation in the importance of maintenance activities and their effect on the structural integrity. Activity urgency takes into account the urgency of repair due to the severity of a deficiency. The importance of the bridge in the road network is taken into account by bridge criticality. Bridge adequacy takes into account the capability of the bridge to safely carry loads.

The prioritisation of bridges for rehabilitation and replacement is based upon the degree to which each bridge is deficient in satisfying the public needs, which are divided in three general categories: level of service capabilities, bridge condition and other related characteristics. Evaluated deficiencies of fore-mentioned categories are then combined to yield a total deficiency rating (TDR). The range of the TDR is from 0 to 100.

There are four characteristics included in the evaluation of deficiencies of level-of-service capabilities. These characteristic deficiencies, for which equations have been developed to calculate their values, are: load carrying capacity (LCD), clear deck width (WD), vertical clearance for traffic carried by the bridge (VCOD) and vertical clearance for traffic passing under the bridge (VCUD). LCD has been developed as a function of the rated load capacity, average daily traffic and detour length. WD is a function of the clear deck width and the average daily traffic per lane. VCOD and VCUD are functions of vertical clearances and average daily traffic. Bridge condition deficiency (BCD) is determined as the sum of the condition deficiencies for the superstructure (SPD), substructure (SBD) and deck (BDD). SPD, SBD and BDD are directly related to the condition rating and are expressed with the equations for each element. Other deficiencies, taken into account are the remaining service life deficiency (RLD), approach roadway alignment deficiency (AAD) and waterway adequacy deficiency (WAD). RLD is determined as a function of condition ratings of the superstructure, substructure and bridge deck. AAD and WAD are directly related to the appraisal rating contained in the database and a function for calculation coefficient is given.

Total Deficiency Rating is calculated by simple equation:

$$TDR = \phi \times (LCD+WD+VCOD+VCUD+BCD+RLD+AAD+WAD).$$

The value of factor ϕ depends upon the functional classification of the highway carried by the bridge. The arrangement of all bridges on the highway system in decreasing order of TDR, results in a prioritised listing. The bridges with the highest TDR values are considered as having the highest priority for rehabilitation or replacement. In order to obtain the final prioritised listings after the TDR has been established for all bridges, the cost of replacement and cost of rehabilitation must be provided. TDR combined with cost information and other factors like average daily traffic, average daily truck traffic and estimates of the economic benefits, yield listings of bridge rehabilitation and replacement projects, which are prioritised in order to enable effective management of the bridge system.

4.0 MATHEMATICAL METHODS

While reviewing the literature on the bridge management optimisation procedures, the papers were found which describe the use of different mathematical methods for optimisation analysis. In this chapter a short review of some papers is made of using these methods in the field of civil engineering. These methods are mainly used for the optimisation of mathematical modelling of different structures, design of reinforced, prestressed and steel structures and only a few papers were found about optimisation used in pavement and bridge management. In the following chapters, a very brief description of three mathematical methods are given, i.e. classical mathematical formulation, neural networks and genetics algorithms. A short review of some papers describing applications of these methods in the field of civil and structural engineering as well as in pavement and bridge management is presented further.

4.1 Classical mathematical formulation

Optimisation that concerns the minimisation of functions (cost functions in bridge management) is pretentious problem. Many different algorithms with classical approach, in this report called as “classic” methods, were developed in the past. Maybe not the most important of them, but the most effective in practical applications, are included in well known programming packages, e.g. MatLab[22]. In this report only the standard functions (algorithms) for minimisation are presented.

Scalar minimisation: $\min\limits_{a} f(a) \text{ such that } a_1 < a < a_2$

Unconstrained minimisation: $\min\limits_{x} f(x)$

Linear programming: $\min\limits_{x} c^T x \text{ such that } Ax \leq b$

Quadratic programming: $\min\limits_{x} \frac{1}{2} x^T H x + c^T x \text{ such that } Ax \leq b$

Constrained minimisation: $\min\limits_{x} f(x) \text{ such that } G(x) \leq 0$

Goal attainment: $\min\limits_{x,\gamma} \gamma \text{ such that } F(x) - w\gamma \leq goal$

Minimax: $\min\limits_{x} \max\limits_{\{F_i\}} \{F_i(x)\} \text{ such that } G(x) \leq 0$

Semi-infinite minimisation: $\min_{x} f(x) \text{ such that } Gx \leq 0, K(x, w) \leq 0 \text{ for all } w$

Different functions (algorithms) can be used for solving the same problem; which one is the most suitable for certain problem, surpass the frame of this project. Note that for completeness, general forms of the equations (definitions) are given. More profound understanding is not necessary for further reading. Reader, interested for more details, can found them in the literature, for example (23,24).

4.2 Neural Networks -ANNs

An ANN takes after its biological analogy through its composition of nodes and the connections among them. The advantages of using ANNs include improvements in the speed of operation by parallel implementation either in hardware or in software.

ANNs are a kind of algorithms with certain characteristics that can be used to solve certain optimisation tasks. The common approach to the construction of optimisation neural networks is to formulate the problem in terms of minimising a cost or energy function - this approach is known as the Hopfield network[(25)]. Self-organising of neurons[(26)] is also an optimisation problem which can be connected to the cost minimisation.

Some attempts have been made in the past to show how the ANNs can be used in Bridge Management Systems. It can be concluded, that the time dimension can be modelled by dynamic programming, whereas the network dimension can be simulated by a neural network. ANNs have the potential to be used in modelling allocation of funds for the bridge stock with a large number of alternative strategies for repair, rehabilitation or replacement.

4.3 Genetic Algorithms - GAs

Genetic algorithms are search algorithms based on the mechanics of natural selection and natural genetics. They combine survival of the fittest among string structures with a structured yet randomised information exchange to form a search algorithm with some innovative flair of human search[(27)]. Genetic algorithms as an optimisation method have achieved increasing popularity as researchers have recognised the shortcomings of calculus-based and enumerative schemes.

Genetic algorithms are different from standard optimisation and search procedures in four ways:

- GAs work with a coding of the parameter set, not the parameters themselves,
- GAs search from a population of points, not a single point,
- GAs use payoff (objective function) information, not derivates or other auxiliary knowledge,
- GAs use probabilistic transition rules, not deterministic rules.

4.4 Review of some applications

4.4.1 Applications of the classical mathematical algorithms

Many results of the research of different optimisations can be directly used in the cost optimisation, which is one of the main concern in bridge management. This fact is very important whereas most of the optimisation applications are focused on the optimisation to (preliminary) design of bridges and other structures.

Lounis and Cohn[28] have presented an approach to the preliminary design of simple span precast pretensioned highway bridge girders using classic mathematical optimisation methods. The bridge design problem was formulated as a nonlinear programming problem and the projected lagrangian algorithm solved it. Several design objectives were investigated either separately or simultaneously with the aim of achieving cost-efficient bridge designs. The approach is used to generate a new set of five optimal girder sections and then to determine the girder spacing and span capability of each precast girder. The study has shown that proposed five new section types are more cost-effective than the corresponding Canadian standard sections because for similar depths they achieve greater span length and girder spacing while requiring less concrete and prestressing steel. The study of bridge design optimisation was formulated based on the design variables (girder section shape and bridge deck cross section), design constraints (Serviceability limit state constraints, ultimate limit state constraints, size constraints for girder shape optimisation) and design objectives (minimum superstructure cost, maximum feasible girder spacing, minimum prestressing force, minimum concrete area of girder section). In the paper it is emphasised that developed program can be implemented with any other type of objective function (e.g., minimisation of girder depth).

A special issue of Microcomputers in Civil Engineering was focused on the Multicriteria Design Optimisation. Multicriteria optimisation techniques are approaches that couple the processes of design and decision making. The resulting solution is a design that is feasible, efficient, or nondominated with regard to all (even conflicting) criteria and ensures the best compromise between all competing criteria. Lounis and Cohn[29] have presented an approach to multicriteria optimisation of engineering structures and structural systems based on the use of the constraint approach for generating efficient solutions and compromise programming for selecting the “best” of satisficing solution. The criteria of minimax and minimum Euclidian distance provide the designer with a rationale for the choice of the best solution. For system optimisation problems, the definition of a dominant criterion and compromise programming lead to a practical approach to the design of large-scale structural systems. In structural design, minimizing structural costs tends to be the dominant objectives. As a result, a practical strategy for system optimisation consists of adopting the structural cost minimization as the dominant (or primary) objective and determining the minimum cost solutions for all alternative systems. Afterwards, the values of other criteria corresponding to these minimum cost designs are computed. If the minimum of the minimum cost solutions of all systems is at least 10% (or some other practical value) more economic than the next minimum cost solution, this solution, referred to as the min-min solution, may be adopted as the optimal design, and all other criteria may be disregarded. However, if there is at least one other competing system that is within the 10% difference range of the min-min solution, selection of the best system is made on the basis of the system performance with regard to all other criteria. On the other hand, if all criteria are relevant but not equally important (i.e., no dominant criterion can be defined), multicriteria optimisation techniques are used to generate the set of Pareto optima (or a nondominated solution) for a multicriteria optimisation problem if there is no feasible solution that may yield a decrease of some objective function without causing a simultaneous increase of at least another objective function. Several methods for generating the set or a subset of Pareto optima of a vector optimisation problem have been proposed in the literature.

Farkas and Jarmai[(30)] have presented in their paper the methodology for designers to select the most suitable structural version considering the cost, mass, and the maximal deflection of a steel box beam structure, which were selected as objective functions. In the cost function, the material and fabrication costs are included. The design constraints related to the bending stress and local buckling of plate elements. The shear-stress constraint and size limitations are also considered. The optimal beam dimensions are computed using several single- and multiobjective optimisation methods. The results of an illustrative numerical example show the effect of yield stress of steel and that of the weighting coefficient. Results also show that mass and the cost function are only slightly conflicting. The deflection minimization leads to maximal prescribed sizes and to a significant increase in cost and mass.

In the paper “Optimisation of Infrastructure System Maintenance and Improvement Policies” Guignier and Madanat[(31)] presents an approach for the joint optimisation of maintenance and improvements of the components of a network of infrastructure facilities such as highway bridges and pavements. In the literature, the maintenance and improvements have often been handled separately, probably because the problems seem quite different and budgets allocated for maintenance and for improvements often come from separate sources. However, these decisions (maintenance and improvements) are not independent due to the presence of trade-offs between the two sets of policies. For example, rather than maintaining a bridge for twenty years before finally replacing it, instead savings can often been achieved by replacing it now or in the near future. In the paper by maintenance are meant actions that retard or correct the deterioration of the facilities, and by improvements are meant actions that alter the functionality of the facility while returning its condition to its best possible condition state. A Markov decision model for the joint optimisation of maintenance and improvements was developed, thus improving the budget allocation among facilities in the network between the two sets of activities and within each set. The model is used to solve the steady-state policies, but relaxes the assumption of age-homogeneous condition-state transition probabilities, which has been criticised in the literature. Moreover, the model allows for the possibility of not exhausting the annual budget available every year, so that part of it can be spent more efficiently in later years. The paper includes a case study, which demonstrates that substantial savings can be achieved through joint optimisation of maintenance and improvements policies.

Frangopol and Estes[(32)] proposes a methodology for a system reliability-based condition evaluation of existing highway bridges. An optimum lifetime repair strategy based on minimum expected costs is developed. The initial optimum repair strategy is updated using both biennial visual inspections and specific non-destructive evaluation testing. The study was made for an existing bridge and it illustrates how system reliability methods can be used to optimise the lifetime repair strategy while minimising total repair cost and maintaining a prescribed level of system reliability. Because the initial strategy is based on assumptions that must be verified over the life of the structure, inspection results can be used to update the reliability of the structure and the repair strategy. With some reasonable assumptions, the biennial visual inspection can be used, but often the information provided is not sufficient, or the condition states are not well enough defined to update the reliability. The reliability update of a structure can be completed with much greater confidence if specific non-destructive evaluation techniques are used to provide the relevant information. The proposed method appears to be a useful method to minimise the expected repair costs while assuring a prescribed level of safety.

The goal of optimal lifetime planning of bridge maintenance is to determine and implement the best possible strategy for allocating limited resources to the inspection, maintenance, rehabilitation and replacement of bridges. In the study presented by Frangopol and Estes(33) proposes a general methodology for determining the optimal lifetime planning of bridge inspection and repair programs based on minimizing the expected costs while maintaining an acceptable level of reliability. The proposed methodology does not address the planning of ordinary inspections, but it is focused on integration of non-destructive evaluation techniques, such as acoustic emission, radar, infrared thermography and half-cell potential, in bridge management. For individual bridges this methodology determines the optimum inspection technique, and the numbers and timing of inspections and repairs. The proposed approach to the problem of lifetime bridge maintenance is shown to be a viable method for optimising inspection and repair investments during the expected remaining life of existing bridges. The optimum strategy has to achieve a balance between lifetime reliability and expected life-cycle costs. In the study the expected total cost is the sum of the expected lifetime inspection cost and the expected lifetime cost of repair. The expected total costs are minimised to find the optimal method of inspection and the optimal inspection times. The time value of money is not considered in this study.

In another paper Estes and Frangopol(34) proposes a system reliability approach for optimising the lifetime repair strategy for highway bridges. The approach is demonstrated on an existing highway bridge. The bridge is modelled as a series-parallel combination of failure modes, and the reliability of the overall bridge system is computed using time-dependent deterioration models and live load models. Based on an established repair criterion, available repair options, repair costs, and updating, the optimum lifetime repair strategy is developed. The sensitivity of the optimum strategy to changes in various problem parameters including the prescribed service life, system failure criterion, and net discount rate is studied. The conclusions reveal that the proposed approach demonstrates real potential for practical applications, needs frequent updates through inspection, and require considerable research effort to develop accurate input data.

Engelund & Sørensen(35) presented in their paper the evaluation of repair and maintenance strategies for concrete coastal bridges on a probabilistic basis. Reliability-based planning of repair and maintenance is based on a statistical analysis of the problem. Uncertainties related to inherent physical uncertainties, statistical uncertainties and model uncertainties are taken into account in the formulation of a probabilistic model. The model makes it possible to determine the probability that a given repair strategy is used at a given time. By including all costs of implementation of relevant repair strategies and taking the current interest rates into account, the probabilistic approach makes it possible to select the optimal for assessment and repair in a rational way. In an example a determination of the optimal strategy for repair and maintenance of a coastal bridge pier is presented. Initially a traditional analysis is performed that indicates the optimal strategy is to perform the repair when major signs of corrosion are visible. A decision analysis gives the result that a preventative repair strategy is optimal. Because both analyses are based on different estimates of the time when the repair strategies are implemented, they yield different results. This only emphasised the need for an accurate method of predicting these times. From the given example it is evident that the probabilistic method is more suitable than the traditional approach because the random variation of the variables can be taken into account in a rational manner. However, the results of a reliability-based analysis depends on the prior beliefs of the decision-maker to some extent. Therefore, the authors conclude, the decision analysis should be seen as a basis to support a given decision, rather than a method that always leads to optimal decision.

Gannon, Weyers and Cady(36) emphasised in their paper that cost information on chemical and physical techniques for concrete bridge protection and rehabilitation constitutes an essential component in determining life-cycle costs for ranking alternative protection and rehabilitation techniques. Cost data were obtained from bid tabulations and were then converted to mid-1991 national average values by using publishing cost indexes. The national average cost data for each protection and rehabilitation treatment were then subjected to detailed statistical analysis to develop cost models reflecting the effects of four independent variables: work quantity, number of bids, total contract cost, and cost of maintenance and protection of traffic. Eight combinations of these four variables were developed to be independent variables in the regression analysis. In the study an inverse power model was used. The ultimate choice of factors in each case rested with the regression coefficient (R^2). Cost information were developed for seven systems, such as: deck patching, deck protection systems, experimental deck protection systems, structural patching, structural protection systems, "new" deck protection systems, and "new" structural patching. To make valid comparisons among patching and protection systems by life-cycle cost analysis it was necessary that the cost be consistent and composed of appropriate cost components. These included engineering costs, installation costs, user costs, effects on the regional economy, and environmental impact. Not all cost components are applicable in all situations. For a given treatment the applicable cost components will depend on whether the work is accomplished by contract or maintenance force account. It was also evident that some components would vary widely as functions of additional factors. Examples include maintenance and protection of traffic, which is primarily dictated by traffic volume, and contractor-related costs, which are heavily influenced by work volume at the site and regional business climate. Two basic approaches can be used to acquire a required cost information. The first involves the use of classical engineering estimating techniques, the second approach is the empirical procedure involving the systematic examination and evaluation of archival cost data. The problem of the latter approach is that there is usually insufficient documentation of details regarding components of the cost figures. Based on the statistical analysis and engineering estimation equations were developed to predict the cost of the rehabilitation treatments. At the end of the paper the authors stressed that caution should be exercised when using developed models in predicting costs. Since most of equations have an inverse term these models will result in a very high price for small quantities. Therefore judgement should be used before applying the costs to a life-cycle cost model.

4.4.2 Applications of the Neural Networks

Some attempts have been made in the past to show how the ANNs can be used in Bridge Management Systems. Mohamed et al[37] have presented the network structure for bridge management which is basically a Hopfield network with two layers, but with a dynamic penalty parameter. The common approach to the construction of optimisation neural networks is to formulate the problem in terms of minimising a cost or energy function. Two main steps should be followed in mapping an optimisation problem onto a neural network that uses an energy function: the first step is to choose a network architecture that decodes neurons' outputs into a solution to the problem, in the second step an energy function is formulated that generates the best solutions at its minima. Energy functions resemble penalty functions in operation research. The developed ANN for the study of Mohamed et al consists of two layers. The first one has two neurons, corresponding to penalty parameter and the second layer has a massively connected neurons, which represent the total number of bridges and the number of improvement alternatives for each bridge. Each neuron will receive four inputs, and these are feedback input from itself, input from all other neurons, input from neurons representing alternatives for the same bridge, and the benefit loss due to the alternative that the neuron represents. The costs of improvement alternatives will represent the weights of the neuron connections. The energy function is represented by two functions, the first one is the objective function (the benefit loss for any year t) and the second one is the penalty function. The penalty function has two terms, the first one represents the budget constraints whereas the second term represent the constraints, which ensure that for every bridge one and only one alternative should be selected. The form of penalty function is such that it will ensure that the penalty function will have its lowest value when all the constraints are satisfied, otherwise it will be greater. In the paper they presented two examples (bridge "stock" of two and of ten bridges) by using artificial data, where the constraints were the limited budget. The conclusions based on the presented study are as follows: The bridge problem has two dimensions. The time dimension can be modelled by dynamic programming, whereas the network dimension can be simulated by a neural network; ANNs can be easily and effectively used to allocate a budget to bridge projects; The developed ANNs have the potential to be used to allocate funds for large number of bridges with unlimited viable alternatives.

Pompe and Feelders[38] made a comparison between the performance of linear discriminant analysis, classification trees, and neural networks in predicting corporate bankruptcy. A proper statistical design was used to test whether observed differences in predictive performance are statistically significant. Using rigorous statistical testing, they were not able to conclude that in the case of the data set studied, one learning method clearly outperforms the other methods.

Nakatsuji et al[39] used neural network model for description of macroscopic relationships among traffic flow variables. The relationship among traffic flow variables play important roles in traffic engineering. They re used not only in analysis of traffic flow behaviour but also in some macroscopic traffic flow simulation models. The authors presented a procedure for describing the macroscopic relationships among the traffic flow variables using some neural network models. First model was a Kohonen feature map which was introduced to convert original observed data points into fewer, more uniformly distributed ones. This conversion improved regression precision and computational efficiency. Then multi-layer neural network model was introduced as a second model to describe the two-dimensional nonlinear and discontinuous characteristics among traffic flow variables.

Chou et al[40] have presented a novel approach of applying the theory of fuzzy sets and moment invariants to analyse pavement images. By applying the theory of fuzzy sets and calculating moment invariants from different types of distress, features are obtained (This is important, because there are some close relations between fuzzy set methods and neural networks[41]). Then, a back-propagation neural network is used to classify these features. In the study, presented in the paper, a fuzzy enhancement algorithm, moment invariant features, and neural networks were used to classify pavement cracks (alligator cracks, longitudinal cracks, transverse cracks, combination of longitudinal and transversal cracks, diagonal cracks, and nondistress). Moment invariants are shown to be feasible for pavement crack classification. Although the shape of the pavement crack is irregular and fuzzy, which results in the loss of invariant properties, moment invariants still perform well. The extracted features are input to the neural network, and the classification accuracy is quite satisfactory. Using different criteria in the crack density to determine severity between alligator and other types of cracks provides more reasonable results, concluded the authors.

Cattan and Mohamadi[42] presented in their paper the analysis of bridge condition rating using neural networks. Paper describes the application of neural network systems in developing the relation between subjective ratings and bridge parameters as well as that between subjective and analytical ratings. It is shown that neural networks can be trained and used successfully in estimating a rating based on bridge parameters. From the results of the study presented by the authors, the use of neural networks is promising and should be investigated further. They stated that it would also be interesting to study the historical degradation of a bridge using neural networks. If rating data for a given bridge exist over several years, certain degradation patterns may be identified. The capability of neural networks in controlling the bias in rating values need to be studied further.

Christian and Pandeya[43] described in a paper a research work on analysis and predicting the operating and maintenance costs of a number of facilities. The design and construction of the facilities were different in many ways although the facilities served a similar function. Differences were observed in the operating and maintenance costs. The authors stressed that it is extremely important to analyse total ownership costs and recognise the factors, which govern them when costs and conditions are changing. Some of the factors which affect total ownership costs are: facility location, facility type, facility height, design technology, material quality, price indices, interest rates and budgetary conditions. The analysis was conducted on the set of data for operating and maintenance costs over the last twenty years for fourteen universities and eight government office facilities. For the research feedforward neural network models were developed using the Neural Network toolbox in the Matlab software package. Training and testing sets of data were created for two sets of period. In both cases, however, the relatively small number of data points and their high eccentricity precluded a high degree of accuracy to the cost – time profiles. It was therefore not possible to consider the effect of non-uniform rates of change in the cost – time profiles, and the degree of non-uniformity.

4.4.3 Applications of the Genetic Algorithms

Liu at al[44] developed a method, based on a simple genetic algorithm with two additional techniques, Paretto optimality ranking and fitness sharing. It was implemented for the deck rehabilitation plan of network-level bridges, aiming to minimise the total rehabilitation cost and deterioration degree. The genetic algorithm was chosen, because of the complicated relationship between the rehabilitation cost and deterioration degree of infrastructure systems is most easily introduced by the method, where the number of solutions can be captured simultaneously and easily incorporate the concept of Pareto optimality.

Jenkins[45] in his paper described the ideas behind the concept of genetic search and outlined the basic principles of the genetic algorithm. His observations are: GA is an effective tool in engineering problems requiring an efficient search of combinatorial space; a space-condensation heuristic assist the GA in finding an improved result and reducing the processing time needed; adaptation of controls also assists the GA but appears to be less important than the space-condensation heuristic; constraint handling using simple penalty function is satisfactory and can include a practical tolerance in use; the built-in controls allow the user to choose a slow, high-quality solution or a faster, low quality solution; low quality settings give near-optimal results sufficient for practical purposes.

Hajela et al[46] described the use of genetic algorithms in determining the optimal layout and sizing of two- and three-dimensional grillage structures for stress, displacement, and element buckling constraints. These problems have highly non-convex design spaces that effectively preclude use of more traditional mathematical programming approach. A two-level genetic algorithm-based search is used, wherein the kinematic stability constraints are imposed at one level, followed by the treatment of stress and displacement constraints at a second level of optimisation. Since genetic algorithms search for an optimal design from a discrete set of alternatives in the design space, their adaptation in the topologic design problem is natural and is governed only by issues related to computational efficiency.

Koumousis and Arsenis[47] employed genetic algorithms to perform the optimal detailed design of reinforced concrete members of multi-story buildings. Used genetic algorithms were based on a roulette wheel reproduction scheme, single multiple-point and uniform crossover, and constant or variable mutation schemes. The method presented decides the detailed design on the basis of a multi-criterion objective that represents a compromise between a minimum weight design, a maximum uniformity, and the minimum number of bars for a group of members. By varying the weighting factors, designs of different characteristics result.

Design optimisation of reinforced concrete plane frames using genetic algorithm-based methodology was presented by Rajeev & Krishnamoorthy[48]. Emphasis was placed on genetic modelling aspects, which provide mechanisms for considering realistically the practically issues, resulting in a rigorous optimal design model providing rational solutions.

Gero and Louis[49] adopted approach that encode the formulation in a genetic algorithm and that allow the formulation to evolve in the direction of improving Pareto optimal designs. A set of rules (in the form of a shape grammar), the execution of which produces a design, was encoded as the genes in a genetic algorithm. The rule set was allowed to evolve, not just the order the execution of rules. Presented example have demonstrated the approach and its utility in improving Pareto optimal designs.

Ohmachi et al(50) have proposed a method for formulation and quantification of human subjective evaluations and uncertain numerical values by using multiple hyperplanes in multidimensional spaces. The article is interesting because they employed a genetic algorithm as a search method for optimal formulations - it was proved to be very effective.

Furuta et al(51) have presented a decision-making supporting system for quantifying the aesthetic factors of bridge structures, which is based on a genetic algorithms and computer graphics. Genetic algorithms are applicable to produce many design alternatives, and in order to evaluate these alternatives, the concept of a psycho-vector is used for quantification the aesthetic factors.

Soh and Yang(52) have presented an approach to the layout and shape-optimisation problem of bridge truss structures using genetic algorithms. The objective was to find an optimal layout design that will have minimum weight or material volume, subject to performance constraints related to member stresses, joint displacements, and member buckling. An automated two-stage optimisation search process, which integrates structural analysis by finite-element method, genetic algorithms, and cognitive topology patterns, was developed to solve the optimal problem.

Chikata et al(53) presented a paper where inverse analysis by neural networks of scenery evaluation of planted concrete structures was examined. Comparison of the efficiency of neural network inverse analysis and genetic algorithm analysis using fuzzy-set theory in reproduction of the same scenery evaluation questionnaire's results shows the same level of accuracy. However, the neural network offers more advantages for such kind of problems.

Kumar and Adeli(54) wrote a paper which was concerned with the development of a distributed algorithm for minimum weight design of large structures on a network of workstations using (biologically inspired) genetic algorithms. The high scalability of the distributed genetic algorithm demonstrated that a cluster of workstations provides a cost-effective alternative for high performance computing for coarse-grained applications such as the GA-based structural design.

5.0 RECOMMENDATIONS

Optimisation of the maintenance strategies of bridge structures has becoming more and more important in the last few decades. It is the result of the increasing number of bridge structures in the bridge stock, poor maintenance in the past, a condition of a considerable number of bridges is not satisfactory, and there is a constant lack of funds to implement needed maintenance. As a consequence, procedures have been developed to carry out the optimisation of maintenance work. Some of them are based on the engineering judgement, some of them are completely computerised and some of them are partly computerised with the final engineering judgement.

The review of the literature has shown that there are only a small fraction of papers dealing with optimisation of maintenance strategies. Several methods have been developed for the optimisation of maintenance strategies for minimising the costs of the repair work or the expected life-cycle costs. Methods use different mathematical tools to solve the problem. Methods, however, are only as good as the input values for costs, modelling and random variables[32].

Modelling and implementing effective optimisation procedures need a lot of data from the past and present activities in maintenance and repair work. Therefore it is recommended for systematic collection of all relevant data and information. This systematic collection of data should be focused on:

- Observation of developing deterioration process with time of the original construction as well as the repair work. The environmental conditions should be taken into account.
- The quality of the executed work at the time of construction.
- The type as well as the quality of the past and present executed repair or maintenance option.
- Evaluation of the effectiveness of the implemented past repair work. It should take into account the condition at the time of evaluation and time it passed since its application.
- Effectiveness of the inspection time periods and NDT used to evaluate the condition of the structure as well as the repair work. The results can be used for optimisation of the inspection time intervals as well as the type of the inspections.
- Analysis of the past optimisation maintenance strategies and how the present condition of the structure is in concordance with the predicted one by the optimisation procedure.
- Typical repair work.
- Results of the load tests of the bridge structures.
- Increase of load over time.
- Results of the destructive and non-destructive testing of bridge structure components.
- The replacement value of the structure.
- All costs, which have a minor or a greater influence on optimisation of maintenance strategies. Direct and indirect costs should be taken into account. The influence of each type of costs on optimisation should be analysed.
- All parameters which may influence the optimisation process (importance of the bridge structure and the network, importance of the location of the bridge in the network and for the local community, volume of the traffic on the road, load restrictions, age, ….).

All these data should be structured in such a way that they can be directly stored in a data bank of the management system and that they can be easily manipulated for different purposes of management system, in which the optimisation of maintenance strategies is one of the most important. Proposed optimisation methods should be analysed on a bridge stock of real structures and of different types of structures.

6.0 CONCLUSIONS

Optimisation of maintenance options or strategies is a very important module in a Bridge Management System. They have evolved from the early procedures based only on engineering judgement to very sophisticated ones based on the classical mathematical formulations or artificial intelligence, such as Neural Networks and Genetic Algorithms. The evolution of the sophisticated (computerised) optimisation methods was also the consequence of the development of high-speed computers. The usefulness of the optimisation methods depends on input variables of the costs, modelling and other random variables. Therefore, further research in this area is needed (modelling of deterioration rate; influence of different types of costs on the results of life-cycle maintenance and decision making; analysis of different repair techniques, their durability and cost effectiveness; analysis of life-cycle maintenance options on large numbers of real and different type of structures; parametric studies of different mathematical formulation of life-cycle optimisation on the same stock of structures) as well as the systematic collection of all relevant data, which influence the optimisation of maintenance strategies.

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